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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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Among papers to appear in forthcoming issues of the *Journal* are the following:

Sedimentary petrology of the Sunda Shelf. By F. A. van Baren and H. Kiel

Heavy residues from lower Triassic conglomerates, New South Wales. By Dorothy Carroll and Roy Brewer

Laminated beach sand. By K. O. Emery and R. E. Stevenson

Pennsylvanian sedimentation in northeastern Socorro County, New Mexico. By Raymond Sidwell and G. Frederick Warn

Authigenic albite in the Green River oil shales. By Fred E. Moore

Sorting of Canadian River, Oklahoma, sands. By William F. Tanner and Paula Mallams

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FIGS. 1–3, SEPTEMBER, 1950

THE PETROLOGY OF A SPECIMEN OF THE PERRY FARM SHALE

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ABSTRACT

A specimen of the Perry Farm shale collected in Ray County, Missouri, was found to be a calcareous, micaceous sandy shale. Lamination is due to the essentially parallel orientation of platy minerals; micas, chlorite, illite, and kaolinite. Quartz, potash feldspar, and plagioclase with small amounts of tourmaline, zircon, rutile, and sphene comprise the major part of the sand-silt fraction. The coarse clay fraction contains sericite, chlorite, and kaolinite, whereas illite predominates (with a little montmorillonite) in the finer clay. Extensive laboratory evidence is given for the determination of the clay minerals. The marine origin of the shale is discussed in terms of its mineralogy.

INTRODUCTION

Detailed mineralogical examinations of sedimentary rocks are basic to erecting a sound sedimentary petrology (Krynine, 1950). In comparison to a relatively voluminous literature on igneous rock mineralogy, the published studies of sedimentary rocks are scanty. Mineralogical studies of clay shales especially, are fewer than those of the other sediments because the work on clay minerals is tedious. With the thought that more data on sedimentary rock mineralogy should be put on record, this report is offered on the petrology of a specimen of the Perry Farm shale.

FIELD OBSERVATIONS

The Perry Farm shale, the middle member of the Lenapah formation, was named by J. M. Jewett (1941) from the type section, 1.5 miles west of Angola, Labette County, Kansas. The specimen material for this study was collected where Missouri State Highway 10 crosses the west branch of Crooked River in Ray County, T. 52 N., R. 29 W. This exposure has been tentatively correlated with the Perry Farm shale by W. Howe, working under Walter V. Searight of the Missouri Geological Survey. The Perry Farm shale is about 14 feet thick in Ray County, Missouri, where it consists of soft, dark blue-gray to black laminated shale interspersed with lenses of siltstone and fine-grained sandstone. Most of the shale weathers to drab to yellowish gray color, except a 3 foot portion near the top which may be mottled red and green and which weathers to a red soil. The specimen studied is a gray, calcareous, micaceous, laminated sandy shale which appeared to be typical and representative of the Perry Farm. It was collected near the top of the exposure at the locality cited.

LABORATORY PROCEDURE

The Perry Farm shale was examined in thin section, and disaggregated so that light and heavy minerals of the sand-silt fractions could be separated and determined. The clay portion was further sized into three fractions on which were made differential thermal analyses, X-ray diffraction patterns, electron micrographs, and infrared absorption measurements.

One kilogram of shale was treated with 1 N acetic acid (less drastic than mineral acids) in excess to remove carbonates. The residue was washed with distilled water and centrifuged. It was dispersed by machine-shaking in water to which 2 ml of concentrated NH_4OH was added per 1500 ml of water. Sand was removed

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on a 225 mesh (0.061 mm) Tyler sieve while the wet-sieved, silt-clay suspension was run into a sedimentation bottle.

The silt fraction, 61 to 4 microns in diameter, and the coarse clay fraction 4 to 1 micron, were separated and segregated from the finer clay by conventional gravity sedimentation. The remaining clay fraction (particles less than one micron effective diameter) was fractionated by means of a Sharples centrifuge into 1 to 0.2 micron, and less than 0.2 micron effective diameter sizes. The latter are referred to as the medium and fine clay fractions.

The sand and silt fractions were split down using a Jones-type splitter and separated into heavy and light portions by using tetrabrom-ethane which was adjusted to float quartz. Division of the silt size was accelerated by centrifugation of the heavy liquid. Removal of the heavy fraction from the bottom of the centrifuge tube was facilitated by grinding off the tapered end of a 20 ml centrifuge tube to leave a hole 1 mm in diameter at the bottom and inserting the tube into a flat-faced rubber stopper. The centrifuge tube is nearly filled with liquid and the upper end also stoppered during separation.

Quartz, K-feldspar, and plagioclase were separated by the use of selective stains as follows. After blowing the grains onto molten resin coating a glass slide, they were exposed to fumes of concentrated HF for 5 to 10 minutes. Next they were immmersed in one per cent aqueous solution of malachite green for 5 minutes, rinsed, immersed in a saturated solution of sodium cobaltinitrite for 5 minutes, rinsed, and dried. Quartz remains unchanged, plagioclase stains green, and K-feldspar yellowish. Adding the malachite green before the sodium cobaltinitrite produces a better discriminatory stain than adding them in reverse order (Ting, 1950; Gabriel and Cox, 1929; Russell, 1935; Willman, 1942.)

THE MINERAL DETERMINATIONS

Thin section.—In thin section cut across the lamination, the Perry Farm shale shows rude parallelism of mineral layers and flakes of the platy minerals. The latter, which are pleochroic biotite, chlorite, white mica, and clay, form a matrix in which are distributed more or less fine-grained quartz, feldspar and other minerals. Carbonate (chiefly calcite) is disseminated in tiny ("stardust" between crossed nicols) particles, in larger subhedral grains, and in irregular patches. Iron oxides, pyrite, and carbon constitute the opaque minerals.

The thinnest part of the sections show most of the coarser clastic grains separated from each other by clay and micas. Although sand-rich and clay-rich layers may be interspersed, graded bedding is not evident.

Clastic and non-clastic fractions.—A gross distribution of the clastic and non-clastic fractions of the shale was determined as is tabulated below. The carbonate was found to be almost entirely calcite.

	Weight per cent
Carbonate (acid soluble)	12.4
Sand (200-61 microns diam.)	34.0
Silt (61-4 microns diam.)	40.0
Coarse clay (4-1 microns)	5.4
Medium clay (1–0.2 microns)	6.0
Fine clay (less than 0.2 microns)	2.2
	100.0

Sand Fraction.—(34 weight per cent of the rock). Quartz makes up 78 per cent (grain count) of the sand fraction. Grain shape ranges fron angular to well rounded but the angular to sub-angular shapes predominate by far. Angularity is original or produced by fracture; angularity due to secondary enlargement is uncommon. The quartz is colorless in the main, but a few rose-colored grains are present. Acicular inclusions, rutile and tourmaline (?), are most common, and oval-shaped zircon (?) and irregular gas bubbles are also included in the quartz.

Quartz containing predominantly acicular and irregular inclusions is most likely to have come from an igneous (probably granitic) provenance (Mackie,

1899; Keller and Littlefield, 1950). Those grains which were rounded and surface-pitted probably were derived from sandstones.

Orthoclase and microcline constitute about 8 per cent (grain count) of the sand fraction. They are angular to sub-angular, and altered to an advanced stage to clay.

Plagioclase, ranging from albite to labradorite, comprises about 13 per cent (grain count) of the sand fraction. Alteration (to sericite and zeolite?) is less advanced in the plagioclase than in the K-feldspar.

The heavy minerals make up about 0.8 per cent by weight of the sand fraction. Biotite in hexagonal to ragged-edged cleavage flakes constitutes about 45 per cent (grain count) of the heavy fraction. It is usually light to deep brown except where altered to light green. Needles of rutile (?) are included in some flakes. On the fresher mineral, $2V$ is very small, $N_g = N_m = 1.60$, $B = 0.03$.

Chlorite comprises about 40 per cent (grain count) of the heavy mineral fraction. It is pale to deep green, and N_m ranges from 1.585 to 1.595.

Muscovite in hexagonal shaped flakes with more or less rounded edges, and in irregular shaped flakes makes up about 12 per cent (grain count) of the heavy mineral fraction. Indices of refraction were found to include $N_g = 1.598$, $N_m = 1.594$, $B = 0.03$. A few of the flakes contain included needles of rutile (?). Micas are characteristic of many Pennsylvanian-age sandstones, and might reveal highly significant information if they were studied carefully.

Tourmaline is sparingly (2 per cent) represented by brown and green varieties, brown predominating. Most grains are prismatic crystals with varied terminations, but a few are fractured and rounded.

Zircon is also sparingly present in stout prisms and oval shaped grains.

Scanty opaque iron oxides, pyrite, and leucoxene-coated grains complete the heavy mineral assemblage of the sand fraction.

Silt fraction.—(40 weight per cent of the rock.) The silt fraction is composed of quartz and feldspar as follows:

	Per cent grain count
Potash feldspar	6
Plagioclase	10
Quartz	84
	100

The heavy minerals constitute about 0.7 per cent by weight of the silt fraction. They are distributed as follows:

	Per cent grain count
Chloritic material	45
Biotite	24
Muscovite	19
Tourmaline	7
Zircon	4
Rutile, Sphene, Opaques	1
	100

The heavy minerals of the silt fraction are largely similar to those of the sand fraction. In addition, sericite with lower indices, $N_m = 1.575 - 1.592$, than the muscovite of the sand fraction was separated from the muscovite. The tourmaline occurs in occasional pink and colorless grains, but green and brown predominate. The tourmaline grains are mainly prisms terminated with rhombohedra on one end and truncated on the other. Such euhedral crystals suggest first cycle (or nearly so) derivation from igneous rocks. Zircon grains occur as both euhedral and rounded grains. These shapes have been conventionally interpreted as being derived from igneous and multi-cycle sedimentary rocks, respectively, but question may be raised as to adequate observational basis for such interpretation,

It is noteworthy that the heavy minerals consist almost entirely of the micas (biotite, chlorite, muscovite) and the resistant tourmaline-zircon pair. Amphiboles, pyroxene, garnet and other less resistant minerals are conspicuously absent. The possibility that lesser resistant heavy minerals were originally present and subsequently removed by solution

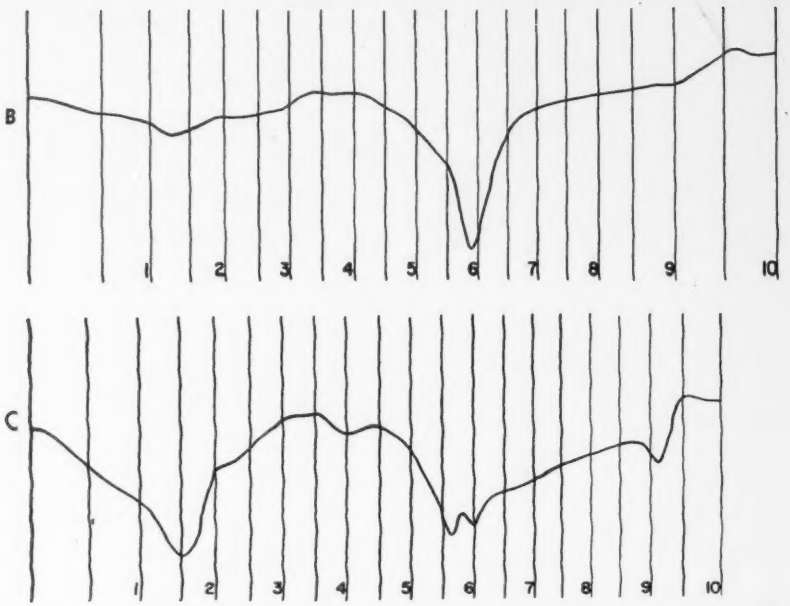

FIG. 1.—Differential thermal analysis curves of the medium clay fraction, Curve B; and of the fine clay fraction, Curve C. Slightly different heating rates for the two specimens account for the variation of lengths in the two curves, which are reproduced here without compensatory modification.

must be entertained, but the impervious nature of the shale surrounding the sand makes appreciable solution effects in the shale exceedingly doubtful. Because of the absence of the mafic minerals, and the prevalence of zircon and tourmaline, it appears from the heavy minerals that the provenance of the Perry Farm source materials was sedimentary, which differs from the evidence of the light fraction. Sedimentary petrology needs more certain diagnostic evidence. The abundance of micas in Pennsylvanian age rocks, as has been mentioned previously, seems to the writers to be a fertile field for investigation.

Coarse clay fraction.—(5.4 per cent by weight, 4-1 microns in diameter.) Although this size fraction approaches the resolving limit of the microscope, considerable reliable information on indices of refraction, texture, morphology, and color of the particles may be obtained. Kaolinite was determined as the mineral in the particles with low birefringence and indices of refraction about 1.565. Colorless mineral shreds with indices 1.560–1.585 are probably sericite. Greenish flakes, almost isotropic, with index of refraction about 1.610 are chlorite. Quartz is recognized by its extinction and indices in the range about 1.550. The D.T.A. (differential thermal analysis) curve shows an endothermic peak at 980°C, typical of kaolinite. A small exothermic rise between 300° and 340°C. is attributed to organic matter. Hence, it is concluded that kaolinite, chlorite, sericite, and quartz comprise the coarse clay fraction.

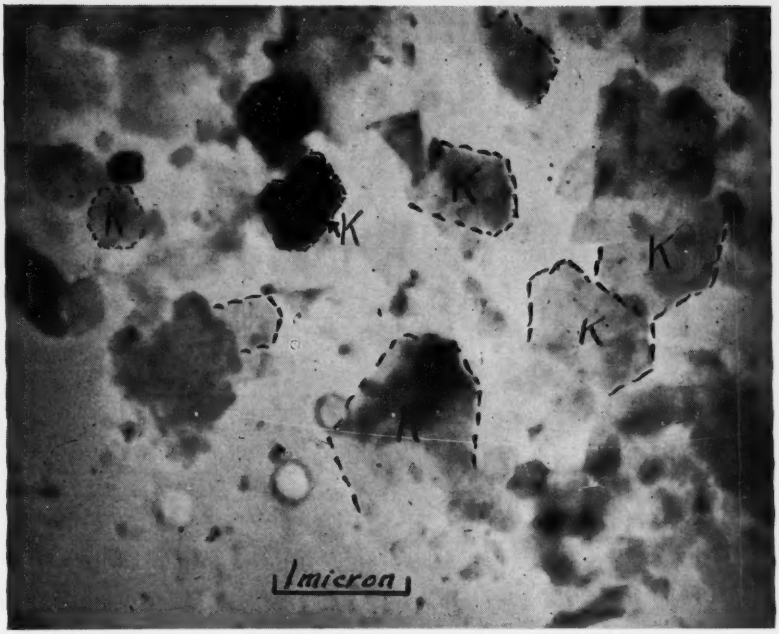

FIG. 2.—Electron micrograph of the medium clay fraction. The relatively faint, hexagonal-shaped outlines of the kaolinite crystals are indicated by dotted lines in the photographic print. A scale representing one micron is at the bottom of the photo.

Medium clay fraction.—(6 per cent by weight, 1–0.2 micron in diameter.) The medium clay fraction appears under the microscope as a yellowish aggregate with indices ranging from 1.570 to 1.590. Evaporation of a drop of the suspension does not give a clay film from which can be obtained diagnostic optical properties. Nevertheless, the indices of refraction of the medium clay aggregate fall within those of the mixtures of the major clay groups.

The D.T.A. curve shows broadly defined endothermic changes below 300°C., an exothermic rise between 340° and 415°C., a very pronounced endothermic peak at 585°C., and an exothermic peak at 960°C. (See fig. 1.) A mixture of clay minerals is indicated, with either the illite or montmorillonite groups giving rise to the endothermic reaction below 300°C., and the kaolinite group being responsible for the 585°C. endothermic and the 960°C. exothermic peaks.

An electron micrograph shows at 23,000 × magnification, subangular to hexagonal shaped flakes which are interpreted as kaolinite, and an abundance of relatively featureless finer particles which may be illite or montmorillonite. (See fig. 2.)

An X-ray powder diffraction pattern of the medium clay fraction shows a very weak diffuse d/n spacing at about 14.5 A which may represent a small amount of montmorillonite or of a mineral of the chlorite family. A weak line at 9.88 A is interpreted as illite, and a very strong line at 7.19 A represents kaolinite. A small amount of quartz is indicated by

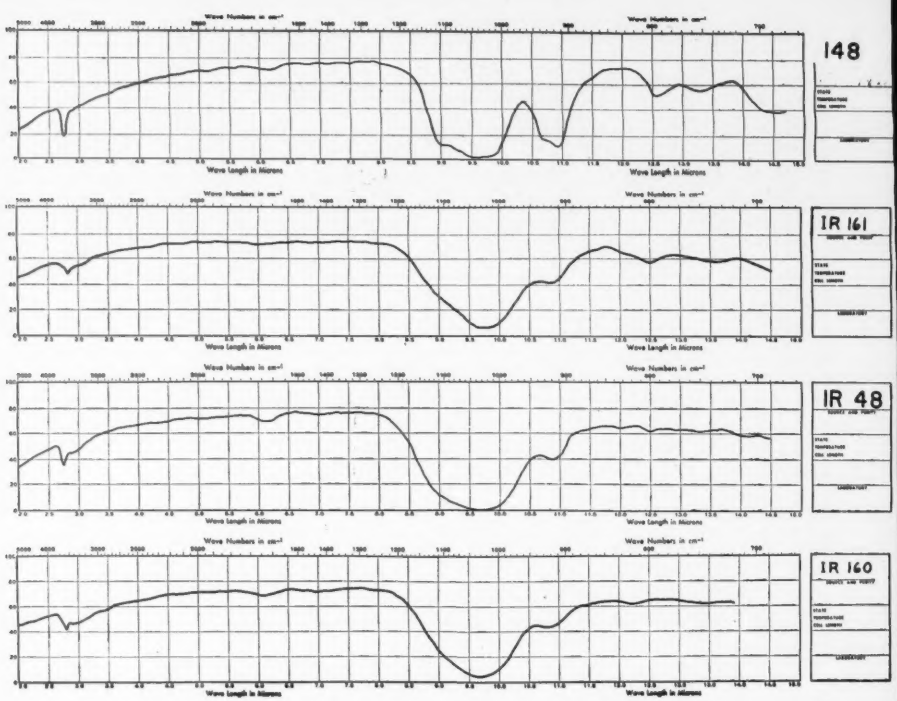

FIG. 3.—Infra red absorption spectrogram of: South Carolina (Bath) Kaolinite, 148. Medium clay fraction, Perry Farm shale, IR 161. Illinois (Fithian) Illite, IR 48. Fine clay fraction, Perry Farm shale, IR160. Per cent transmission is plotted on the ordinate and the wave length, in microns along the abscissa.

a medium line at 3.35 A (the strong line of quartz). Seventeen other lines on the film support the above interpretation of the 001 "reflection" for the clays, and that (1011) of quartz.

Infrared absorption spectrograms may be used to differentiate kaolin group minerals from the 3-layer clay minerals (Keller and Pickett, 1950). The medium clay fraction shows in its spectrogram, absorptions characteristic of both kaolinite and illite. To facilitate comparisons, the infrared absorption spectrogram of the medium clay fraction, IR161, is illustrated between those of South Carolina kaolinite, No. 148, and Fithian, Illinois, illite, IR 48. (See fig. 3.)

Beginning comparison at the left (2 micron) end, the usual monomeric OH bonding of clays is shown typically by the sharp peak at 2.75 to 2.8 microns. From 2.8 to 3.1 microns, the medium clay fraction exhibits definite polymeric OH absorption which occurs in illite but very scantily (if at all) in kaolinite. The spectrogram of IR 161 differs from illite, and resembles kaolinite in a subdued way, by its absorption peaks at 12.5 and 13.5 microns. Hence, the evidence from infrared absorption coincides with that from other techniques.

The spectrograms reproduced herein were drawn from measurements on clay alone (not suspended in Nujol), and are

therefore free from the supplementary and somewhat distracting Nujol absorptions seen in the earlier curves published (Keller and Pickett, 1950).

There is little doubt that the medium clay fraction is composed of kaolinite and illite (the former predominating), a smaller amount of chlorite probably, or montmorillonite, and some quartz.

Fine clay fraction.—(2.2 per cent by weight, less than 0.2 micron in effective diameter). The fine clay fraction is yellowish under the microscope. An evaporated film gives aggregate or "sigma" (Grim, 1934; Merwin and Posnjak, 1938) indices $N_g' = 1.592$, $N_p' = 1.562$, biaxial negative, very small optic angle. These data suggest illite.

The D.T.A. curve (C, fig. 1.) shows a large broad endothermic peak at 150°C., a small endothermic depression between 350°–450°C., doublet peaks superimposed on the major endothermic reaction at 560° and 600°C., and a twin endothermic-exothermic peak pair at 910°–950°C. The curve is characteristic of illite, with probably a little goethite shown by the 350–450°C. endothermic reaction. The curve for a doublet variation at 560° and 600°C., is not understood.

Electron micrographs of the fine fraction show only relatively featureless particles which are usually representative of ordinary illite or montmorillonite.

The X-ray powder diffraction pattern of the fine clay fraction shows very close correlation of all d/A lines with those of illite. Hence this fraction of the Perry Farm shale is probably almost pure illite, so far as purity of illite goes. A faintly discernible line at 3.35 A, corresponding to the strong line of quartz, indicates that a tiny amount of quartz persists even to sizes less than 0.2 micron in diameter.

Comparison of the d/n lines of the fine fraction of the clay with those of type illite are given below to emphasize the mineral purity of the fine clay fraction and its close resemblance to the type.

Perry Farm shale fine fraction		Illite (A.S.T.M. X-ray index cards)	
d/n A	Intensity	d/n A	Intensity
10.32	ss	10.0	10
7.09	ww		
4.96	w	4.96	4
4.47	ss	4.46	10
		4.11	2
		3.64	2
		3.40	2
3.35	ww (quartz)		
2.57	ss	2.56	10
		2.44	4
very faint		2.37	5
2.25	m	2.24	6
very faint		2.18	4
		2.12	4
1.99	m	1.99	5
1.65	m	1.65	3
		1.64	5
1.51	s	1.50	9
		1.38	4
1.30	m	1.30	5
1.248	w	1.25	4

The infrared absorption curve of the fine clay fraction, IR 160 (fig. 3), closely parallels that of illite from Fithian, Illinois, IR 48. The most diagnostic absorption occurs in the range 2.75 to 3.2 microns which is supported by confirmatory similarity along the remainder of the curve.

The base exchange capacity of this clay fraction was determined to be 35 milli-equivalents per 100 grams of dry clay, a value which is characteristic of illite.

It is concluded without doubt that the fine clay fraction of the Perry Farm shale is composed of illite with a very small amount of quartz.

MINOR ELEMENT ANALYSIS OF THE MEDIUM AND FINE CLAY FRACTIONS

Portions of the medium and fine clay fractions were mixed in the ratio in which they occur in the shale, and the mixture was analyzed by emission spectrography. A sample was burned in a graphite arc, using the "cathode layer" method of excitation. The light was dispersed in a Jarrell-Ash 480 cm grating spectrograph, and photographed on

plates in comparison with synthetic standards of known composition. Semi-quantitative estimates with an accuracy of ±50 per cent are possible. The analysis of the minor elements is given below in terms of the elements (not oxides).

Element	Percentage	Element	Percentage
Mn	0.1	V	0.05
Mo	0.0005	Ba	0.03
Zn	0.01	Sr	0.05
Cu	0.005	Sn	0.001
Co	0.003	Hg	—[1]
B	0.005	Sb	—
Pb	0.02	Li	—
Ag	0.0001	Cd	—
Ti	0.3	Ge	—
Ni	0.0003	Bi	—
Cr	0.05	Be	—

[1] Looked for but not detected.

ORIGIN OF THE PERRY FARM SHALE

A marine origin for the Perry Farm shale has been established by the presence of brachiopods, molluscs, and corals in it. High illite content in argillaceous sediment suggests marine sedimentation, but, in contradiction, abundant kaolinite in an ancient sediment "would suggest that it was not deposited under marine condition." (Grim, Dietz and Bradley, 1949). However, the occurrence of kaolinite in the coarse and medium clay fractions, and illite in the medium and fine clay fractions of the Perry Farm shale may not be as contradictory of depositional environments (if the suggestions of Grim, Dietz and Bradley are followed) as appears at first glance. Because Pennsylvanian age sedimentation was characterized by oscillations closely above and below sea level, and lateral gradations between subaqueous and subaerial deposits, the mineralogy of Pennsylvanian sediments logically may be mixtures of minerals characteristic of the two depositional environments.

The textural relationship between the kaolinite and illite is not determinable, and therefore a genetic interpretation based on observation is not possible. However, several possible relationships may be considered.

Possibly the relatively coarse kaolinite crystals and particles are interspersed at random within an illite matrix like boulders in a conglomeratic sandstone. If so, the question arises, was the mixture deposited as such, or has there been alteration of kaolinite to illite, or vice versa since deposition? Post-depositional alteration of kaolinite is improbable.

It seems more probable that kaolinite crystals were mixed with montmorillonite, degraded illite, or hydrated alumina-silica gel en route to deposition, and that illite or a pre-illite flocculate was deposited upon contact with saline marine water sufficiently rich in potash to occasion its fixation (Keller, 1946). The fixation of potassium consequent upon the maturing of illite crystals may have progressed during diagenesis. Sediments composed of illite tend to have a laminated texture (Grim and Cuthbert, 1945).

The clay mineralogy of the Perry Farm shale is consistent with deposition in a marine environment as prevailed during Pennsylvanian time.

The source localities and materials for the Perry Farm shale are conjectural, both as to provenance and geographic location. Evidence from the light (sp. gr.) minerals of the sand fraction suggests an igneous source (probably granitic) removed hardly more than one erosional cycle from the shale. Moreover, kaolinite which occurs in the shale commonly weathers from granite (potash feldspar), or in an environment where efficient leaching and oxidation prevails. On the other hand, some rounded sand grains and the tourmaline-zircon heavy mineral suite, without less resistant representatives, indicate a sedimentary source. Both igneous and sedimentary sources may have contributed. Too little is known about the meaning of the relatively abundant micas in the Pennsylvanian sediments to base an interpretation of any appreciable security on them.

One might look toward the St. Francis Mountains of southeast Missouri, to the Nemaha ridge, or to land areas in Arkansas or Oklahoma as sources, but the writers have not recognized any mineralogical evidence which points specifically in any direction. The occurrence of Perry Farm shale across Kansas into Oklahoma suggests, merely on geographic convenience, a source area west or south of Ray County, Missouri. Perhaps a study of the shale from other localities might make possible the derivation of its paleogeography, but the mineralogy from a single locality is not very revealing.

SUMMARY

A specimen of typical Perry Farm Shale, collected in T. 52 N., R. 29 W., Ray County, Missouri, may be described as a plastic, dark-bluish gray, finely laminated, calcareous, micaceous, sandy shale. Its mineral composition is tabulated as follows:

Carbonate, chiefly calcite, 12.4 per cent by weight.
Sand, 200-61 microns diameter, 34 per cent by weight.
- Quartz 78 per cent grain count of the sand
- K—feldspar 8 per cent count of the sand
- Plagioclase 13 per cent count of the sand
- Heavy Minerals 0.8 per cent by weight
  - Biotite 45 per cent grain count of heavy minerals
  - Chlorite 40 per cent grain count of heavy minerals
  - Muscovite 12 per cent grain count of heavy minerals
  - Tourmaline 1 per cent grain count of heavy minerals
  - Rutile, sphene and opaques 1 per cent grain count of heavy minerals

Silt, 61-4 microns diameter, 40 per cent by weight.
- Quartz 83 per cent grain count of the silt
- K-feldspar 6 per cent grain count of the silt
- Plagioclase 10 per cent grain count of the silt
- Heavy minerals 0.7 per cent by weight of the silt
  - Chloritic material 45 per cent grain count of heavy minerals
  - Biotite 24 per cent grain count of heavy minerals
  - Muscovite 19 per cent grain count of heavy minerals
  - Tourmaline 7 per cent grain count of heavy minerals
  - Zircon 4 per cent grain count of heavy minerals
  - Rutile, sphene and opaques 1 per cent of heavy minerals

Coarse clay, 4-1 microns diameter, 5.4 per cent by weight.
- Kaolinite—abundant
- Chlorite—moderate
- Sericite—moderate
- Quartz—moderate

Medium clay, 1–0.2 micron diameter, 6 per cent by weight.
- Kaolinite—moderate
- Illite—moderate
- Chlorite or possibly montmorillonite—minor
- Quartz—slight

Fine clay, less than 0.2 micron diameter, 2.2 per cent by weight
- Illite
- Quartz slight trace

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 20, NO. 3, PP. 133–147
FIGS. 1–6, SEPTEMBER, 1950

INITIAL SHAPE AND ROUNDNESS OF SEDIMENTARY ROCK MINERAL PARTICLES OF SAND SIZE

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ABSTRACT

Measurements have been made of the size, circularity (two dimensional sphericity) and roundness of crushed and screened fragments of nine minerals of sand size commonly found in sedimentary rocks. These are regarded as the initial size, shape, and roundness before abrasion in ball mills. These are calcite, andalusite, quartz, garnet, zircon, tourmaline, microcline, sillimanite, and hornblende. While abrasion modifies the shape of grains, "the end shape . . . appears to be determined by its original shape." (See Pettijohn, 1949, p. 54.)

It was found that each mineral possesses its own set of characteristics. These are related to type of cleavage and tenacity possessed by each mineral, but the relationships are not simple.

Sizing by screening introduces an element of shape. Similarly, microscopic measurements reflect a different aspect of shape due to preferred orientation of grains on the slide. Such measurements are essentially two dimensional. The frequency distribution is given as per cent by number, so the results may be more applicable to similar measurements in the study of sedimentary rocks in the form of thin section. A discussion of the various methods is given.

Studies of abrasion of minerals in laboratory apparatus, such as ball mills, should recognize that each mineral has its own characteristics. Details of these differences are shown in table 9.

INTRODUCTION

Studies of abrasion of sedimentary particles in laboratory apparatus, such as ball mills, start with fractured material and thus proceed towards smaller and more rounded grains. Many of these results have been plotted. They show, in general, that they are asymptotic in character. The rate at which these results are obtained is related to the rigor of the process.

This paper is based upon microscopic measurements on nine minerals commonly found in sedimentary rocks. These observations were upon freshly fractured material which had not been subjected to abrasion in the ball mills. Consequently they represent conditions prevailing at the start of such experimental runs.

It was found that each mineral has its own characteristics and that *they are not the same.* It is obvious that to regulate these data to "zero" and to assume all start the same ignores the fact that initial shapes, while modified by abrasion, are often reflected in the end results, as seen in sedimentary rocks.

Inasmuch as the nine minerals differ among themselves, in matters of shape, circularity (two dimensional sphericity) and roundness even for a given size, the use of rock fragments instead of minerals was abandoned. Many of such abrasion experiments deal with large sizes in spite of the fact that the bulk of sedimentary rocks are composed of sand and silt sizes. Here the range of sand, as measured as loose grains in two dimensions, has been investigated.

The shape of these fragments was found to differ greatly. This was measured as circularity. Screening was used in bulk sizing which considerably affected the resulting measurement of shape. Consequently some attention was given to the shape of screened and unscreened fragments. Cleavage and tenacity are partly responsible for shape, but they must be considered in three dimensions.

As the shape of grains influences to a large degree the resulting orientation of such grains and orientation affects the planar structure and subsequently the ability of rocks to split, hence fissility,

this matter was given attention. Petrofabric studies of undeformed sedimentary rocks are not common but those that are available contributed to our understanding of bedded sediments.

Some roundness is primary and not exclusively due to abrasion. Some fragments of quartz exhibit high roundness values, while others are very angular. Conchoidal fracture, alone, can produce high roundness of quartz.

Considerable interdependence between these characteristics requires the relating all these measurements to size. When the number of such variables is three, the need for three dimensional diagrams is evident.

tion curves were not identical. It was formerly thought that these differences, expressed in terms of the position and height of the modes, as well as the spread of the base, were due to technical errors, such as the measurement of an insufficient number of grains or imperfections in the microsplit. Repetition of these measurements emphasized the lack of agreement. These are shown in figure 1. The differences are now regarded as definite.

METHODS OF MEASUREMENT

The mineral fragments were sized by screening. The size chosen was −40+60 mesh. The size of the individual grains

TABLE 1.—*The variables*

	Independent	Dependent	Dependent	Dimensions	Figure
1	Size	Frequency distribution of size		2	1
2	Size	Circularity	Frequency distribution of circularity	3	2
3	Size	Roundness	Frequency distribution of roundness	3	
4	Size	Average circularity, screened		2	3
5	Size	Average circularity, unscreened		2	3
6	Size	Average roundness		2	4
7		Average roundness	Average circularity		

GENERAL STATEMENT

The stratification of sedimentary rocks is due to many factors (Ingram, 1948). The orientation of the constituent particles is undoubtedly one of the main causes. This in turn is partly dependent upon the shape of the grains. It is generally realized that mineral cleavage has something to do with the resulting shape of the grains. These planes of lesser strength, as defined by planes in the crystal lattices, determine the planes of separation, and contribute to the lack of tenacity.

During laboratory experimenting (Alling, 1944, p. 105) with the abrasion of fragments of various minerals, it was found that the size-frequency distribu-

was measured microscopically by using the diaphragm method (Alling, 1941). This results in diameters; diameters of circles whose areas are equal to the areas of the grains. In other words, two methods were employed, one by screening and the other microscopically, which give slightly different results. The factor that produces the differences is the shape of the grains. Shaking screens permits elongated grains to up-end and pass through, while chunky grains of equivalent size are retained. This peculiarity of screens is well known (Perry, 1949). The microscopic measurements are made on grains lying on a plane surface, hence they possess a special orientation due to their shapes.

TABLE 2.—*Minerals used*

No.	Mineral	Approximate formula	Locality
1	Calcite	$CaCO_3$	Antwerp, New York
2	Andalusite	Al_2SiO_5	Pennington Co., South Dakota
3	Quartz	SiO_2	Pink, Port Henry, New York
4	Garnet	$And_2\ Gros_{14}\ Pyr_{40}\ Alm_{43}\ Spes_1$[1]	Gore Mt., Warren Co., N. Y.
5	Zircon	$ZrSiO_4$	Cardiff Twp., Ontario, Canada
6	Tourmaline	$H_8Na(Fe, Mg)_4Al_8B_4Si_8O_{41}$	Pale Green, San Diego Co., Calif.
7	Microcline	$Mic_{85}Ab_{10}An_5$	Spruce Pine, North Carolina
8	Sillimanite	Al_2SiO_5	Near Custer, South Dakota
9	Hornblende	$NaCa_2(Mg, Fe)_4Al_3Si_6O_{22}(OH)_2$	Renfrew Co., Ontario, Canada

[1] Kreiger, 1937; Levin, 1948.

Both methods are of value in sedimentary petrography. Screens can be used for unconsolidated sediments, but not for sedimentary rocks unless they are disaggregated. Microscopic measurements can be employed in both cases, thin sections being used in the case of sedimentary rocks. The use of thin sections means, of course, that they are two dimensional measurements based upon random sections and the results are of the order of 75 per cent of the measurements of loose grains. Screening reflects the shape of the grain; microscopic methods, using loose fragments, approach three dimensions, still flat discs orient themselves on the microscopic slide because of shape.

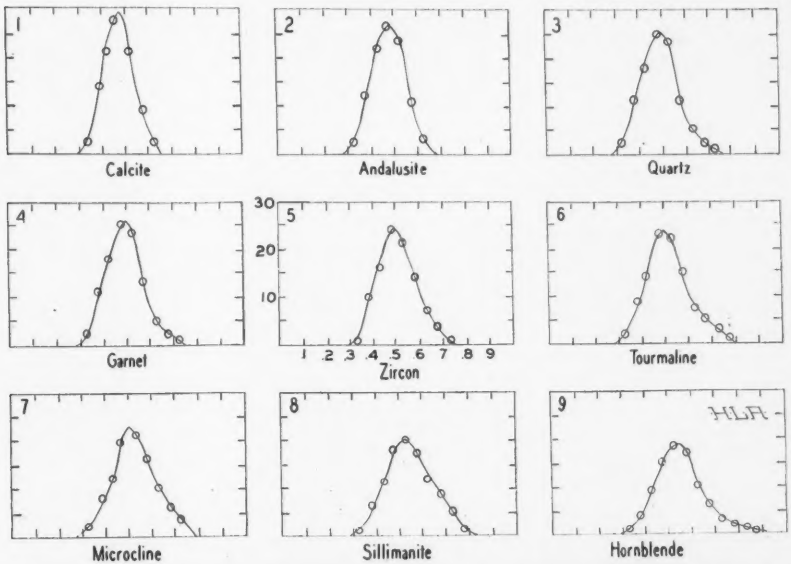

FIG. 1.—Size-frequency distribution curves, percent by number of grains, of the nine minerals. Arranged in order of decreasing mode values and circularity of unscreened grains. Screen size −40+60 mesh. Size measurements by the microscopic-diaphragm method.

Lacking, as we do, accurate conversional constants (although they are approximately known), the three methods are not strictly comparable. This, fortunately however, provides a means of appreciating the general shape of grains of minerals, even though it is not a detailed one.

SAMPLING AND TREATMENT OF RAW DATA

Generalizations regarding the initial shapes of mineral grains, fractured by a hammer on an anvil, depend upon representative samples and the way the raw data are treated.

A microsplit was devised by rotating the bottom pan of the set of screens on a vertical axis into which the fragments were slowly poured. The centrifugal force threw the grains to the periphery of the pan. A complete section of this ridge was removed by a narrow spatula. This proved to be satisfactory.

The choice of fragments measured by the microscope was made by a mechanical stage, using the method of intercepts. This reduces the personal factor. The raw data were plotted and smoothed curves were drawn and values read from the curves. These values were read to the nearest whole number. The combination of these techniques gave satisfactory results.

INITIAL SHAPES

Fracturing mineral specimens in this manner may not imitate nature, yet it can be assumed in most cases that the resulting grains represent a close approach to maximum irregularity, angularity, and the least amount of rounding, etc. At least this is the status at the beginning of the study of abrasion in the laboratory.

DEPENDENCE UPON SIZE

All measurements, (1) size distribution, (2) circularity, (3) roundness, and (4) splinteriness, were made according to size. It has been abundantly demonstrated that this must be done, because very small grains are rarely rounded (Twenhofel, 1939), while large ones can be. To record the roundness without specifying size means very little. This is equally true of circularity as well. Plumley (1948, p. 559) says: "although sphericity [circularity] and roundness are geometrically dissimilar properties, they are both functions of grain size and thus must be functions of each other . . . Russell and Taylor (1937, pp. 225–267) establish this correlation for sands of the Mississippi River, and Pettijohn and Lundahl (1943, pp. 69–78) found similar relations to exist in Lake Erie beach sands."

MEASUREMENT OF SIZE

Size was measured by the diaphragm method (Alling, 1941). A camera lucida projected the image of the grain upon the diaphragm. A light beneath the diaphragm illuminated a scale of concentric circles, each of which delimited a class interval. These were drawn on onion-skin paper, cemented on discs of celluloid.

With these three scales it was possible to measure all fragments with the grade scale of sand devised by the author, 0.1–1.0 mm (Alling, 1943, pp. 266, 269).

The number of grains measured for each curve varied. The number was judged to be sufficiently consistent with the time consumed in measurement. The actual number of grains is given in table 4.

MEASUREMENT OF CIRCULARITY

This is two dimensional sphericity. The method used was based upon the diagrams of sphericity devised by Rittenhouse (1943, pp. 80–81) and transferred to a long strip of tracing cloth mounted on rollers like a piano-player roll. Using the camera lucida, the image of the grains was superimposed upon that of the diagrams of the circularity. By rotating the rollers, the diagrams passed into view until that which most closely matched the grain was found. Hence the circularity was established by comparison.

TABLE 3.—*Scales used with the diaphragm in measurements of size*

Scale #1			Scale #2			Scale #3		
Magnification ×122 Objective ×5 Ocular ×12.5			×91.2 ×5 ×10			×89.7 ×5 ×7.5		
Class interval	Microsc. Diam. mm	Actual Diam. mm	Class interval	Microsc. Diam. mm	Actual Diam. mm	Class interval	Microsc. Diam. mm	Actual Diam. mm
1	0.05	6.1	1	0.05	4.6	1	0.10	8.9
2	0.10	12.2	2	0.10	9.1	2	0.20	17.8
3	0.15	18.3	3	0.15	13.7	3	0.30	26.7
4	0.20	24.4	4	0.20	18.2	4	0.40	35.6
5	0.25	30.5	5	0.25	22.8	5	0.50	44.5
6	0.30	36.6	6	0.30	27.4	6	0.60	53.4
7	0.35	42.7	7	0.35	31.9	7	0.70	62.3
8	0.40	48.8	8	0.40	36.5	8	0.80	71.2
9	0.45	54.9	9	0.45	41.0	9	0.90	80.1
10	0.50	61.0	10	0.50	45.6	10	1.00	89.0
11	0.55	67.1	11	0.55	50.2	11	1.10	97.9
12	0.60	73.2	12	0.60	54.7			
			13	0 65	59.3			
			14	0.70	63.8			
			15	0.75	68.4			
			16	0.80	73.0			
			17	0.85	77.5			

TABLE 4.—*Number of grains measured*

Curve	1 Calcite	2 Andalusite	3 Quartz	4 Garnet	5 Zircon	6 Tourmaline	7 Microcline	8 Sillimanite	9 Hornblende	Total
Size Freq. Dis.	63	104	88	56	91	84	80	71	85	722
Circularity unscreened	262	309	515	217	305	186	396	250	272	2612
Circularity screened	115	111	113	109	114	100	130	135	181	1108
Roundness	135	94	219	371	115	321	147	135	252	1789
Total	575	618	935	753	625	691	753	591	790	6231

Rittenhouse's series of diagrams range from 0.45 to 0.97 sphericity in steps of 0.02. As many of the mineral fragments have a circularity less than his, it was necessary to extend the series down to the 0.29 value. Furthermore, the diagrams were grouped into 11 class intervals with limits as follows: 0.29, 0.31, 0.37, 0.43, 0.49, 0.55, 0.61, 0.73, 0.79, 0.85, 0.91, and 0.97.

The class intervals for size in these measurements were limited by the following: 0, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, and 1.0 diameters in millimeters.

The diaphragm was set for each of these size ranges and the circularity of a sufficient number of grains was measured to establish satisfactory frequency-distribution curves. Consequently for each mineral, data for seven or more frequency-distribution curves, each for a different size range, were obtained. Thus a three dimensional diagram is possible

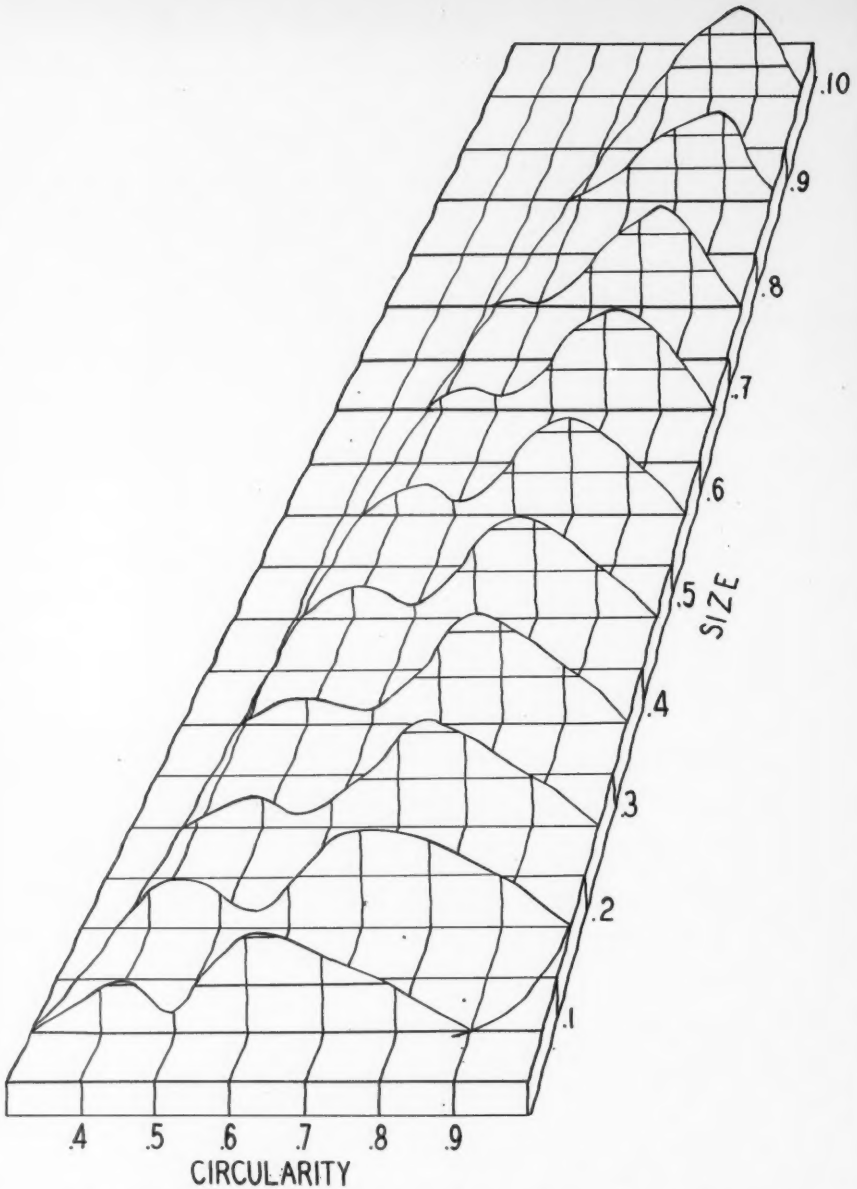

FIG. 2.—Three dimensional diagram consisting of ten circularity-frequency-distribution curves of quartz. The east-west axis is circularity; NNE-SSW scale is size in millimeters. The vertical ordinate is the per cent of frequency by number of grains. Note the presence of supplementary peaks in eight of the curves. These are interpreted as due to the splinteriness of this mineral.

for each mineral. One of these, that for quartz, is shown in figure 2, a drawing constructed like a block diagram with ten frequency-distribution curves as "cross profiles" or "partitions."

The east-west scale is circularity, the northeast-southwest scale is size. The percent frequency-distribution by number is plotted on the vertical axis. Similar block diagrams for the other eight minerals are possible, of course, but that of quartz is regarded as sufficient for the present purpose.

These data, shown in three dimensional drawings, are not suitable for plotting against another variable, hence the circularity for each size range was transformed from two-dimensional curves to single figures by averaging. Of course the mode (or modes) and the median could be used instead. These averages were plotted against size.

SCREENED VERSUS UNSCREENED GRAINS

If the differences between the size-frequency-distribution curves shown in figure 1 are due to differences in shape of the grains, the comparison of the circularity of screened and unscreened grains should be conclusive. This proved to be true. It was found that to secure a completely screened sample it was necessary to shake the screens for at least ten minutes. This is well known.

The comparison of the circularity of screened and unscreened grains is shown in figure 3. Each mineral shows its own characteristics. Because of the use of

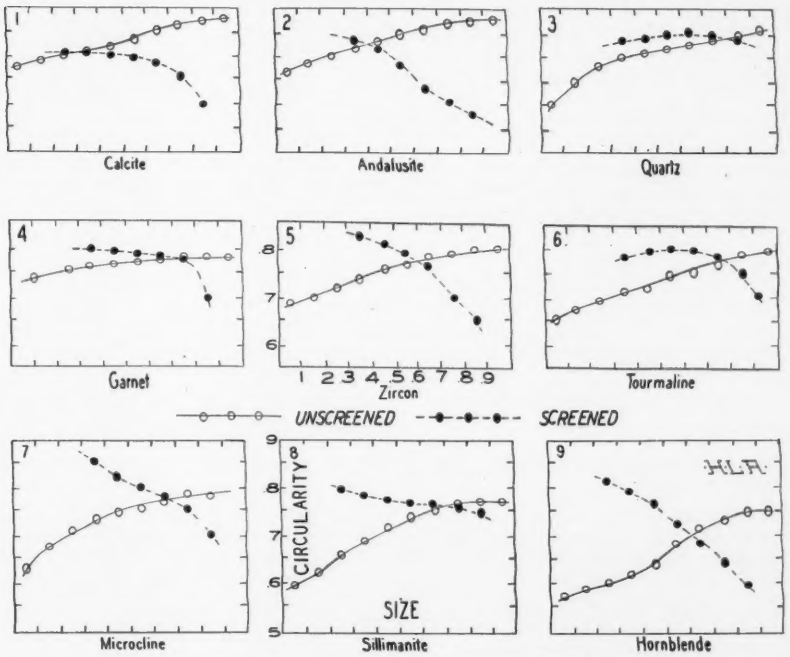

FIG. 3.—The differences between the values of the circularity of screened and unscreened mineral grains. Horizontal axis: size in millimeters, vertical scale: circularity. Screen size −40+60 mesh.

averages in reducing the data of circularity to a single value per each size class interval, some interesting characteristics are thereby lost. One of these is that of quartz. In figure 2, the circularity-frequency-distribution curves ("partitions") of smaller sizes (0.05 to 0.75) show two peaks. These mean that quartz has the habit of fracturing into some small splintery grains with low circularity, while the bulk of them have a higher circularity. The study of thin sections of sedimentary rocks frequently reveals the presence of splinters. These splinters are very effective contributors to the shaly structure of argillaceous rocks, even though few in number. The conchoidal fracture of quartz is so dominant that any true cleavage, probably limited to the β-form, is completely submerged, so it plays little or no part in the shape of clastic grains. It does, however, produce some "rounding." In other words, not all rounding is secondary.

MEASUREMENT OF ROUNDNESS

The roundness of the broken fragments was obtained microscopically by comparison with standard diagrams based upon those devised by Krumbein (1941a), which range from 0.1 to 0.9 in steps of 0.1. This proved to be lacking in sufficient detail for the angular fragments hence the series was subdivided by the author by establishing supplementary diagrams ranging from 0.11 to 0.35 in steps of 0.02. The two series of diagrams interlock and were frequently used together. Like Rittenhouse's diagrams of circularity, Krumbein's series for roundness was drawn on the long strip of tracing cloth and viewed by means of the camera lucida so direct comparison with the image of the grains was effected. Thus by comparison, the roundness was determined. This method proved rapid and a sufficient number of grains could be studied in a reasonable time. The roundness was determined according to size. The size-class interval limits were the same as used for circularity, namely, 0, 0.10 . . . 0.80, 0.90. For each class interval data were obtained for satisfactory frequency-distribution curves. Single values for roundness for each size-class interval were obtained by averaging. These curves are shown in figure 4. The scale used by the author may not be the conventional one; the smallest value was 0.1 and the highest 0.9. Hence, if the scale employed by Pettijohn (1949, p. 51) is desired, the values here given can be converted to the other by the use of table 5.

TABLE 5.—*Conversion scale of roundness*

Scale used 0.1–0.9	Conventional scale 0–1.0
0.1	0
0.2	0.12
0.3	0.25
0.4	0.37
0.5	0.50
0.6	0.62
0.7	0.75
0.8	0.87
0.9	1.00

DISCUSSION OF POSSIBLE WEIGHTED AVERAGES

The number of variables here existing, if all should be considered, would require diagrams in three and four dimensions. Even if the possible ones were drawn and reproduced here a few relationships would perhaps be easier to see, but the majority would not be so evident. Consequently recourse to arithmetical averaging was used. The size-frequency-distribution curves show the percentage, by number, according to size, of course. In measuring both the circularity and the roundness, the data were so taken that the frequency-distributions, by number, according to these properties, were obtained for each size-class interval. Averages of these, per size range, do not reflect the distribution according to size. There are many more intermediate sized grains than those at the extremes. If these averages were weighted by multiplying them by the percent of frequency according to size and the sum calculated

to 100 per cent, more accurate results would be obtained. As the number of small as well as the large are few, however, the characteristics of these would be reduced or obscured by weighting. Hence such a practice was not followed. After all, it is the degree of perfection of circularity and roundness exhibited by these grains rather than the number of such grains that is of interest. To obscure these observations by statistical means does not serve a useful purpose.

RELATION OF SIZE BY DIAPHRAGM-MICROSCOPIC MEANS AND CIRCULARITY

There is a direct relationship between: mode size, mode percentage, mode ratio, median, the first and third quartiles on one hand, and average circularity on the other. The plots are nearly linear. (See fig. 5.)

RELATION OF ROUNDNESS TO CIRCULARITY

As roundness and circularity are functions of size, as Plumley (1948) has pointed out, they are functions of each other. He plotted one against the other. His plot shows a discernible trend, "although the data scatter widely" (p. 560). His graph is linear. The results of this study show the same relationship, but, on the other hand, the graphs are not linear. Each mineral has its own character, and if plotted on the same graph

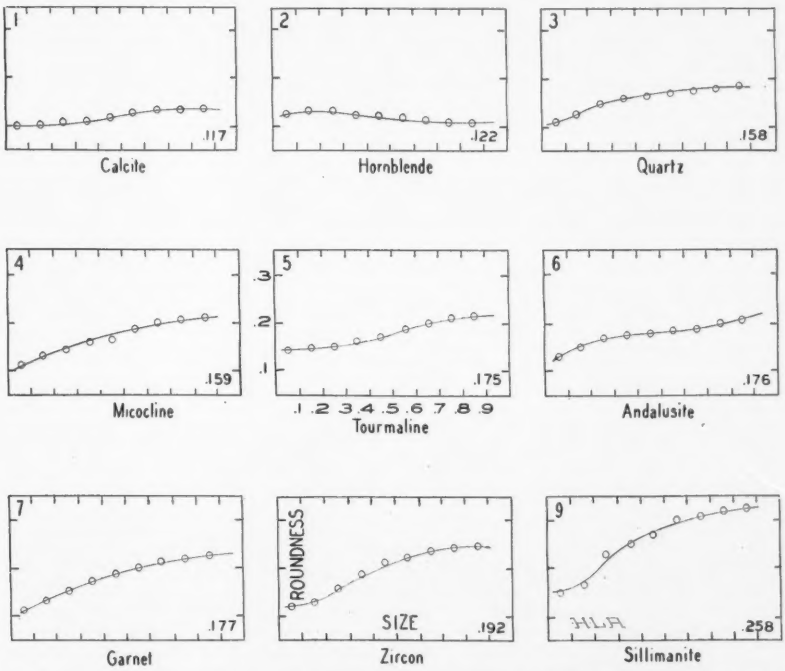

FIG. 4.—Roundness of the nine minerals. Horizontal axis, size in millimeters, vertical scale, roundness. Unscreened grains arranged in order of increasing average roundness, the total averages of which are given. Note the relative high roundness value of sillimanite, which is *initial* roundness.

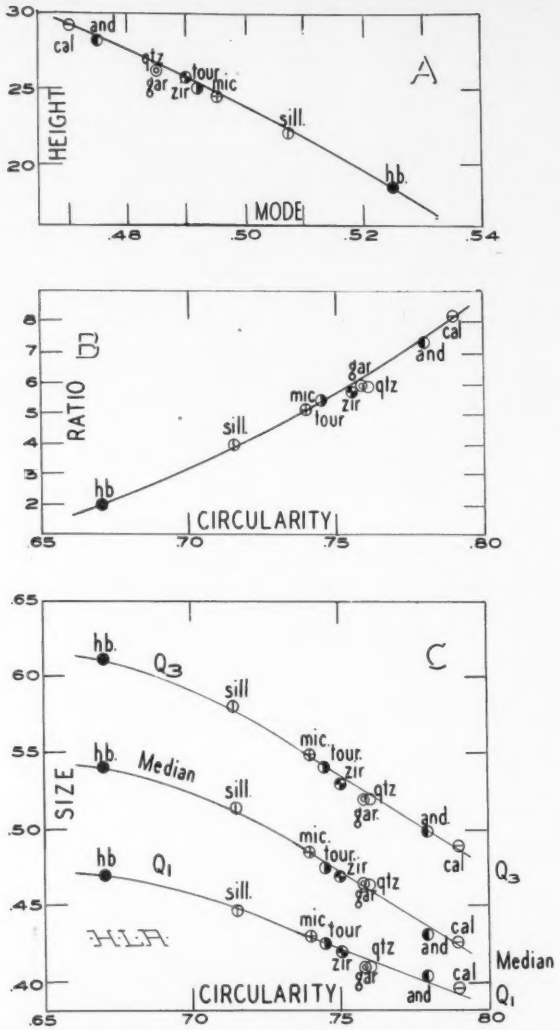

FIG. 5.—Relationships exhibited by the nine minerals. A, Value of mode of the size-frequency distribution curve, horizontal scale and the height of the mode, vertical scale. Relationship nearly linear. Screen size −40+60 mesh. B, Average value of circularity of unscreened grains, horizontal scale, and ratio between height and value of mode of the size-frequency distribution curves, vertical scale. Screen size −40+60 mesh. C, Plot of the median, first and third quartiles from cumulative curves of size-frequency. Note that the same order of minerals is maintained even though one is reversed.

together, they would be widely scattered. Perhaps that in part, at least, explains Plumley's results. What Plumley plotted was "sand" without specifying the minerals present. It is well to note that figure 6 is based upon the initial shapes and roundness of unabraded grains. Plumley plotted grains which had experienced transportation and hence some abrasion. Perhaps there would be greater similarity if the comparison were between abraded grains. Until further work is done this seems to be the present status of the problem. (See Pettijohn, 1949, fig. 105, p. 408.)

DETERMINATION OF SPLINTERINESS

Many of the minerals studied showed characteristic behaviors that were, to a large degree, obscured by averaging the values of the circularity. There are a few thin plates and long needles among the more chunky fragments. As their numbers are few their presence is not apparent in the averaged figures. As these splinters are believed to be factors in producing the foliation of resulting sedimentary rocks, even though few in number, a scheme was devised to bring them into the open so that the differences between the minerals in this respect could be compared.

The plotting of frequency-distribution curves of circularity, one for each class-interval size for the nine minerals, resulted in 90 such diagrams. Those of quartz are shown in figure 2 which illustrates the characteristics of these curves.

Several types of curves were recognized: symmetrical and assymetrical curves; those with narrow and broad bases; those with supplemental peaks and those with

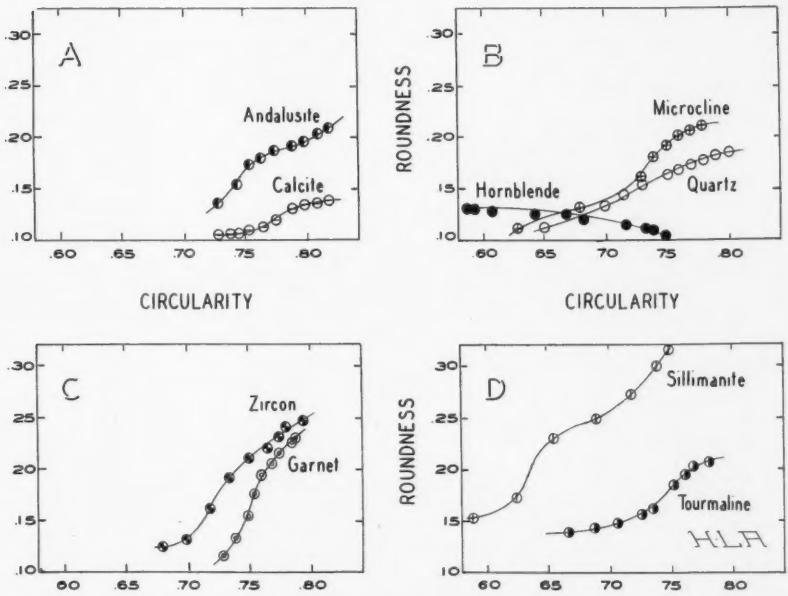

FIG. 6.—Plot of the relationship between circularity and roundness. Note the lack of linear character of the curves. If plotted without regard to specific minerals, the result would be a scatter diagram having only a general trend.

out such departures; and various combinations. Of these, three types were regarded as sufficient for the purpose here: with supplementary peak in the small size ranges (called "P"), assymetrical curves with a "skirt" in the small grain ranges (called "S"), and bell-shaped, symmetrical ones (expressed as "B").

Not desiring to add unnecessarily to the overburdened catalog of special terms, the skewness of frequency-distribution curves was considered. Krumbein (1938) gives the form of measuring skewness as follows:

$$SK_a = \left[\frac{Q_1 + Q_3}{2}\right] - Md$$

As this is based upon cumulative curves, it partakes of the virtues and the disadvantages of such statistical devices. The above formula, involving the two quartiles and the median, cannot be as satisfactory as the frequency-distribution curve in revealing a secondary or supplementary peak. After some experimentation skewness was not used in this study.

Returning to the method of recognizing types of curves ("P," "S," and "B"), table 6 was constructed. While it does introduce a new nomenclature, it, nevertheless, emphasizes what is intended and expresses it in a quantitative manner.

Table 6 can be better understood by noting the columns in which the [2] occurs and the corresponding splinteriness number in the bottom row. This is done in table 7.

TABLE 7.—*Splinteriness of the nine minerals*

Mineral	Splinteriness	Degree
Quartz	8	Most
Microcline	6	
Hornblende	6	
Zircon	5	
Tourmaline	5	
Sillimanite	3	
Calcite	3	
Garnet	2	
Andalusite	2	Least

These results are in line with casual observations, but for the first time, so far as the writer is aware, this characteristic has been measured and nine minerals compared. These results are dependent, however, upon a comparatively few grains involved in the supplementary peaks and hence are subject to some criticism, which in turn suggests further investigation.

It is well to note that this concept is based upon size. Random microscopic

TABLE 6.—*Splinters and circularity of unscreened grains; curve types*

Size, mm[1]	.05	.15	.25	.35	.45	.55	.65	.75	.85
Mineral									
Quartz	P	P	P	P	P	P	P	[2]S	S
Microcline	P	P	S	P	P	[2]S	S	B	B
Hornblende	P	P	P	P	P	[2]S	B	B	B
Zircon	S	S	P	P	[2]S	B	B	B	B
Tourmaline	P	P	P	P	[2]S	S	B	B	B
Sillimanite	P	P	[2]S	S	S	B	B	B	B
Calcite	P	P	[2]S	S	S	B	B	B	B
Garnet	S	[2]B	B	B	B	B	B	B	B
Andalusite	P	[2]S	B	B	B	B	B	B	B
Splinteriness	1	2	3	4	5	6	7	8	9

[1] Mid points of class intervals.
Explanation: P—supplementary peak
S—"skirt"
B—bell-shaped
[2]—marks change in type of curve.

examination supports the belief that most splinters are confined to small sizes. It is well known that reduction in size is more effective in large size ranges; the splinters are believed to represent chips broken off the larger grains.

INDIVIDUAL CHARACTERISTICS

Table 9 gives the values of modes of size-frequency-distribution curves, the average circularity of screened and unscreened grains, and the average roundness and splinteriness of the nine minerals investigated. There are other peculiarities that should be emphasized.

Hornblende.—Because of its dominant cleavage in one direction, hornblende has the lowest values of modes and circularity. It is low in roundness, high in splinteriness, in the sense here employed. In the matter of roundness it is different from all the others; small grains are more round than large ones. No adequate explanation seems forthcoming.

Sillimanite.—Because of its needle-like elongation and its fibrous nature, silli-

TABLE 8.—*Summary of methods of measurement*

Property	Equipment	Size range	Detail (1) mm	Detail (2)	Result
Bulk sizing	Screens	−40+60 mesh	Length of side of opening 0.42 & 0.25	Length of diagonal of opening 0.585 & 0.354 mm	Bulk size by screening
Microscopic size	Diaphragm Alling (1941)	0–1.0 mm Diam. of circles whose areas = areas of grains	Class interval range 0.05	Per cent by number	Freq.-Distrib. & cumulative curves. Mode, median, Q_1 & Q_3
Roundness	Diaphragm. Diagrams based upon Krumbein (1941a)	0–1.0	Class interval range 0.10	By number	Average roundness. Per class interval size
Circularity	Diaphragm. Diagrams based upon Rittenhouse (1943)	0–1.0	Class interval range 0.10	By number	Average circularity. Per class interval size.
Splinteriness	Circularity-Frequency-distribution curves	0–1.0	Class interval range 0.10	By number	Types of curves P, S, & B. Splinteriness numbers from 2–8.

TABLE 9.—*Summary*

Mode size		Circularity screened		Circularity unscreened		Roundness		Splinteriness	
Order	Ave. value	Order	Ave. value	Order	Ave. value	Order	Ave. value	Order	Value
Hornblende	0.205	Hornblende	0.695	Hornblende	0.670	Calcite	0.117	Andalusite	2
Sillimanite	.240	Andalusite	.725	Sillimanite	.715	Hornblende	.122	Garnet	2
Microcline	.258	Calcite	.726	Microcline	.740	Quartz	.158	Calcite	3
Tourmaline	.260	Zircon	.753	Tourmaline	.745	Microcline	.159	Sillimanite	3
Zircon	.267	Sillimanite	.762	Zircon	.750	Tourmaline	.175	Tourmaline	5
Garnet	.268	Garnet	.775	Garnet	.758	Andalusite	.176	Zircon	5
Quartz	.270	Microcline	.782	Quartz	.760	Garnet	.177	Hornblende	6
Andalusite	.275	Tourmaline	.788	Andalusite	.778	Zircon	.192	Microcline	6
Calcite	.290	Quartz	.797	Calcite	.795	Sillimanite	.258	Quartz	8

manite is low in circularity, but perhaps surprisingly, has the highest roundness. The fibers are wrapped around the ends producing a degree of roundness not possible otherwise. This shows that abrasion is not the only factor causing a mineral fragment to become less angular.

In spite of its elongation, it is not particularly noted for its splinteriness.

Microcline.—This mineral has two perfect and one less perfect cleavages. This type of cleavage seems related to the moderate values of the mode, average circularity of unscreened grains, roundness, and the high splinteriness. If the cleavage had been perfect in all three directions, the splinteriness would be low, as it is in calcite.

Tourmaline.—Here the lack of distinct cleavage apparently places tourmaline in the middle of the columns. Evidently this is not the sole cause, as quartz with no cleavage yet produces the most splinters. Is it because of its brittleness?

Zircon.—This mineral behaves very similarly to tourmaline. Its prismatic cleavage is rare.

Garnet.—This mineral is listed as having no cleavage and it occupies a position towards the bottom of the table, while the splinteriness is very low. Fractures are regular and the resulting fragments approach cubical shape. This is in line with its use as an abrasive.

Quartz.—Quartz has a rude rhomboidal cleavage or parting and is situated towards the bottom of the column; its conchoidal fracture results in high splinteriness.

Andalusite.—Andalusite has prismatic cleavage and high mode and circularity values for unscreened grains, and the lowest splinter value. Its behavior is such as to suggest that fracture plays an important part in the shape of these grains. If so, the fracture is nearly equal to that of the cleavage in the ease of separation.

Calcite.—The last mineral has three perfect cleavages; it is at the bottom of the list, with the highest circularity and relatively low splinteriness.

It is possible to make a generalization, which may apply only to these particular nine minerals: that (1) the minerals with one or two dominant cleavages have the lowest circularity as unscreened grains, (2) that minerals with three cleavages possess the highest circularity values, and (3) minerals with no cleavage are intermediate between these extremes; but there are exceptions. The difficulties seem to be that the precise strengths and weaknesses of the various cleavages appear to be inadequately known.

CONCLUSIONS

(1) Studies of the abrasion of sedimentary rock mineral particles should be conducted upon minerals as well as rock fragments. Krumbein's (1941 b) important paper dealt with pieces of limestone. His results are general and not specific. His mathematical discussions are confirmatory and an important contribution.

(2) The nine minerals investigated, before abrasion in ball mills, show widely varying characteristics. To assume they are the same at the start of such experiments is not justified. The individual initial shapes are usually reflected in the shapes of grains in the resulting rock.

(3) Sizing by screens is not entirely satisfactory in that the shape of the grains modifies the results. During the shaking of screens, long grains that otherwise would be retained are up-ended and pass through. This is shown by the differences between the circularity of screened and unscreened grains (fig. 3) and varying modes of the size-frequency-distribution curves (fig. 1).

(4) Measurement of grain size microscopically, such as by the diaphragm method (Alling, 1941), using diameters of circles equal to areas of the grains, partially removes the element of shape. The method uses "projection" size and is essentially a two-dimensional one. Flat and rod-shaped grains assume preferred orientations on the microscope slide and the areas whose images are measured do not represent completely random posi-

tions. This means that the matter of shape has not been eliminated entirely. However, the element of shape due to screening is not the same as the shape due to preferred orientation on the microscopic slide, as is shown by comparing the values of the circularity of screened and unscreened grains. (See fig. 3.) This problem needs further investigation.

(5) While discussing the measurement of size of loose grains, it is well to recognize the problem of determining the size of minerals in sedimentary rocks in thin-sections. Not only are such measurements two-dimensional, but they are based upon random sections. Such results are less than that for whole grains. Krumbein (1938, p. 130) has calculated the reduction for spherical grains to be 23.7 per cent. This is the basis for the author's metric grade scale (Alling, 1943). These relationships are not simple.

(6) Riley (1941) has questioned whether the term "nominal sectional diameter" is applicable to thin sections. This is a matter of definition. What the diaphragm method definitely uses is the diameter of a circle, the area of which is equl to the area of the grain, in two dimensions.

(7) Cleavage, parting, fracture, and tenacity, and indirectly Mohl hardness, are factors in the initial shape of such clastic grains; the relations are far from simple.

(8) The frequency-distribution curves in this paper are percentages of the number of grains, not weight percentages. The purpose is to make the results as applicable as possible to the study of sedimentary rocks in the form of thin sections.

(9) Circularity, roundness, and splinteriness are related to size. These properties, without specifying the size, are of little significance.

(10) Some minerals, as is illustrated by sillimanite, may possess a surprising roundness even for unabraded grains.

(11) The splinteriness of these minerals has been investigated; quartz has the highest value of the nine minerals.

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FIGS. 1–4, SEPTEMBER, 1950

SEDIMENT MOVEMENT IN RELATION TO CURRENT VELOCITY[1]

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ABSTRACT

Experiments in flumes indicate that the type of movement on a bed of sand may be correlated with mean current velocity. The bottom conditions to be expected if a given current acts on a sand of a given grain size in shallow water are shown in graphic form, and the conditions are discussed.

INTRODUCTION

The current velocity required to move particles of a certain size has been the subject of numerous studies by geologists and engineers, but the results remain somewhat equivocal because the many variables which affect the competent velocity have not been sufficiently well evaluated. Despite the large number of investigations of initial movement of particles, and perhaps as a consequence of their lack of agreement, the relation between the current velocity and the occurrence of other bed movement phenomena has been neglected. The present paper is concerned with the current velocities at which ripples are formed and destroyed, at which sediment comes to rest, at which antidune and sheet transportation occur, and at which grains are put in motion on a rippled bed. It is believed that these data may be of interest to geologists, particularly paleogeographers, because in many instances they will permit an accurate evaluation of the velocity of ancient currents.

This study arises from a laboratory investigation of the transportation of bed-load in which about 300 tests were made in a flume at the Woods Hole Oceanographic Institution. The writer is indebted to the Institution for a summer fellowship. Mr. Henry C. Stetson supervised the study and his help and encouragement are gratefully acknowledged. Dr. H. A. Thomas Jr. has kindly guided the writer in the field of hydraulics; however, the writer alone is responsible for the views here presented. The manuscript has been read by Dr. K. O. Emery, Mr. D. L. Inman, Dr. R. S. Dietz, Mr. E. C. Buffington, and Dr. R. Dana Russell, and to them the writer extends his appreciation for the many suggestions which helped to clarify the text. The information contained in this paper was submitted to the Division of Geological Sciences of Harvard University as part of a doctoral dissertation.

[1] Contribution on No. 512 from The Woods Hole Oceanographic Institution.

THE EXPERIMENTS

The flume in the Woods Hole Oceanographic Institution is one foot wide and six feet long, exclusive of a baffle on the upstream side and a sand trap downstream. It is made of planed, unpainted wood except for a centrally located glass window seventeen by fifteen inches in size.

Water used in the tests was drawn through a two inch pipe connected to the fresh water system supplying the town of Woods Hole. The water pressure was found to be constant for the one to three minutes required for individual measurements during each test. Flow within the flume was non-uniform because the bed was not long enough to allow the water surface to become parallel to the bottom. However, the slopes of the water surface and the bed in the upstream half of the flume appeared to be parallel insofar as they could be measured over so short a

distance. All of the observations were confined to this area of essentially uniform flow.

In order to determine the nature of the flow, potassium permanganate solution was introduced into the flume through a fine glass tube. The flow proved to be turbulent at all velocities which were capable of moving sediment.

In a typical experiment, the slope of the bed was fixed, a recess in the bed was filled with sand, and the surface of the sand was smoothed. A tailgate was placed at a predetermined height, and the flume was filled with water in such a way as to not disturb the sand. After flow through the flume was initiated, the velocity was increased by turning a valve a standard amount until some particular bottom phenomenon was observed. The discharge was determined by the increase in the depth of water in a tank of known plan area. It was observed by the rise in a burette tube during an interval timed with a stop watch which read to 0.2 second. While waiting for the discharge tank to fill, the water depth in the flume was measured at the center of the sand bed and also fifty centimeters up and downstream. The temperature of the water was taken at the start of each day's tests and at intervals of about one hour thereafter, but the variation in temperature proved to be negligible.

The mean velocity was calculated from these data by dividing the discharge by the cross-sectional area of the flow. Experimental errors inolved in these determinations of velocity have been found to be less than about three per cent (Menard, 1949.)

COMPETENT VELOCITY

As used in this paper, and as it is usually defined, *competent velocity* means the slowest mean current velocity which is capable of initiating the movement of grains of a given diameter. The critical tractive force (Rubey, 1938), which is a force acting on the grain, and the critical frictional velocity (Inman, 1949), which is a calculated *bottom* velocity, are other parameters of the force or current velocity necessary to initiate motion; they are not *mean* velocities as is the competent velocity. The relative merits of these various criteria have been the subject of an enduring controversy among engineers (see, for example, Chang, 1939), but, on the basis of present experimental knowledge, all three appear to be valid. Any of the criteria evaluated in the laboratory may be applied directly to streams and rivers; however, it is doubtful that competent current velocity, as here defined, has any real significance with regard to the motion of sediment on the bottom of the ocean. Unfortunately it is the only one of the three parameters which is of use to the paleogeographer or stratigrapher. The critical frictional velocity appears to have a valid and unique relation to the initial motion of sediment in modern rivers and seas, but it cannot be used as a measure of ancient currents because it cannot be determined from the size of the particles which were once moved by the currents. The critical tractive force has the same limitation.

A general relation between competent mean current velocity and grain size was established by Hjulstrom (1935). The limited amount of information then available, however, did not permit accurate determinations of the competent mean velocity for any desired grain size. More recent experiments have provided new data which make it possible to establish the competent mean velocity within a few centimeters per second under limited conditions of depth and slope. A synthesis of the observations of Bogardi (1938), Ho (1935), Indri (1936), Menard (1949), Nevin (1946), Tu (1935), and the Linton Hydraulic Laboratory (1938) is presented in graphic form as the competent mean velocity curve in figure 1. The writer has given the details of the construction of this curve in an unpublished dissertation (1949), but for brevity they are omitted here. The competence curve is introduced merely as a line of reference to which the other bottom phenomena may be tied; nevertheless its

limitations must be noted, in that the experimental data apply only to currents less than one meter deep, and to beds with slopes of no more than a few parts in a hundred. *With deeper water or steeper slopes the competent mean velocity may be quite different*, although there are few observations to prove or disprove this concept.

The competence curve is a significant line of reference because the other bottom phenomena do not occur until the bed-load is put in motion, despite the fact that they may be produced by a slower mean current velocity. For example, a sand which is rippled has a lower competent velocity than when it is smooth, but, if originally smooth, it cannot be rippled until the competent velocity for a smooth bed is exceeded.

COMPETENCE ON A RIPPLED SAND BED

The competent velocity for a given grain size on a rippled bottom is less than it is on a smooth one, as may be seen from the data plotted in figure 2. Motion usually begins in the troughs even before it does on the ripple crests, so this phenomenon probably does not occur because the grains on ripples are projecting into areas where the velocity is greater than it would be on a smooth bed. The

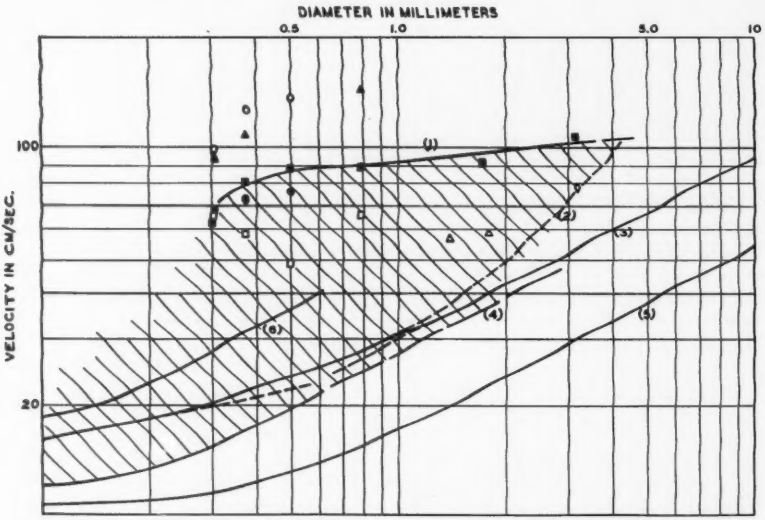

FIG. 1.—Sedimentary processes and bottom conditions in relation to grain size and mean current velocity. (1) Maximum velocity at which sand ripples exist. (2) Maximum grain size on which ripples form. (3) Competence, smooth bed. (4) Competence, rippled bed. (5) Cessation of bed movement. (6) Weak suspension. Individually plotted observations of current velocities and bottom conditions are taken from Gilbert (1914) except where otherwise noted. Open circles, maximum current velocity for antidunes; solid circles, minimum current velocity for antidunes. Open triangles, minimum current velocity for antidunes (Liu, 1937). Solid triangles, maximum velocity for sheet movement; open squares, minimum velocity for sheet movement. Solid squares, maximum current velocity for sand ripples. Open diamonds, maximum velocity for smooth movement. Sand ripples occur only in the shaded area. The observations of maximum current velocity at which antidunes and sheet transportation were seen merely reflect maximum flume capacity, not a change in bottom conditions. Quantitatively, the data apply only to current depths less than one meter, and bottom slopes less than a few parts in a hundred.

explanation may lie in the increased bed roughness which intensifies the turbulence of the flow (USWES, 1935 a).

The difference in the competent velocities on smooth and rippled beds amounts to only three to five centimeters per second, nevertheless, it is sufficient so that transportation of bed-load sometimes may take place on a rippled area of a stream bed while no motion occurs on an adjacent smooth section.

CESSATION OF BED MOVEMENT

Once in motion, sediment continues to move even if the current velocity drops below the competent velocity. Hjulstrom (1935) has discussed this phenomenon, and adopted the experimental results of Schaffernak (1922) for values of the current velocity at which deposition takes place. For all sizes of gravel, Schaffernak found that the deposition velocity was about two thirds of the competent velocity. He tested no materials finer than five millimeters in diameter, but he surmised that the deposition velocity rapidly approached zero for the smaller grain sizes. The present experiments included measurements of the velocity at which all motion ceased for monodisperse sands of 0.059 to 0.71 mm diameter; results are shown in figures 1 and 2. The sands tested all came to rest if the mean current velocity was decreased to about

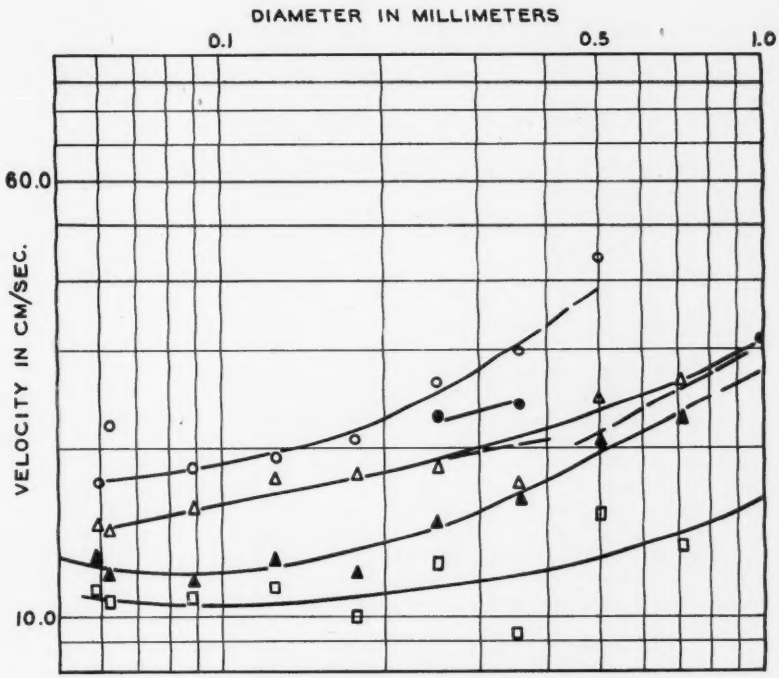

FIG. 2.—Results of the flume tests at the Woods Hole Oceanographic Institution. Open circles, weak suspension. Open triangles, competence on a smooth bed with slope 0.002; solid circles, on a bed slope minus 0.004 (upstream). Solid triangles, competence on a rippled bed. Open squares, cessation of bed movement.

two-thirds of the competent velocity. Even the very fine sand was deposited, although the mean horizontal current velocity was more than ten cm/sec.

The velocities plotted represent deposition of material *transported as bed-load.* The deposition of fine material *transported in suspension* has an entirely different relation to the horizontal velocity. Colloidal material, to take an extreme example, is not deposited even if the velocity is zero. Fine sand settles in water at a velocity which my a be calculated by Stokes law. It stays in suspension, and therefore in motion, only if turbulence is great enough to counteract the settling. Turbulence, however, depends on the hydraulic radius, bed roughness, and the kinematic viscosity as well as the mean velocity; so neither the settling velocity nor the deposition velocity for bed-load is a measure of how slow the mean current velocity must be to permit deposition of material in suspension. A current flowing in a small, straight, smooth-sided watercourse might move fine sand as bedload without being turbulent enough to hold the material in suspension. On the other hand a large river moving too slowly to transport fine sand as bedload might be turbulent enough to keep it in suspension for some time.

There is little valid information on the velocities at which coarse bed load ceases to move. The United States Waterways Experiment Station (1935 b) made a large number of tests on the velocities necessary to sustain the motion of pebbles and cobbles. The rocks were dropped in moving water onto a bed of rough concrete, and a record was made of the lowest current velocity which sufficed to keep them in motion after striking the bed. These results are not entirely comparable with the ones for monodisperse sands, because the bed was not of the material being tested. Friction in the Vicksburg tests would be less and so would the shielding of the test pebble from the impact of the current compared to that which would exist on a monodisperse bed. This disparity is a direct function of the diameter of the pebble; as the diameter increases the measured velocity decreases with regard to the comparable velocity on a monodisperse bed. Data from two series of these tests are shown in figure 3 with the understanding that the slope of the line should be steeper for the reasons cited above.

The present writer used a tidal sluiceway at Sippowisset Beach, a few miles north of Woods Hole on Buzzards Bay, Massachusetts, for some similar tests. The sluiceway is a natural watercourse comparable to a laboratory flume, in that the width, depth, and velocity of the current all vary within a considerable range in accordance with the stage of the tide. With spring tides the width varies from about three to ten meters, the depth from a few centimeters to more than a meter, and the velocity from zero to at least ninety centimeters per second. The portion of the channel used for the tests has a slope of 0.0038.

In a typical experiment, the current velocity was determined, and then cobbles of assorted sizes were thrown a few feet upstream until the largest size which would move was found. Thus, the velocity measured was the minimum one at which moving cobbles would remain in motion, and, as the bottom consisted of sand, the tests were similar to those at Vicksburg. The results of these experiments are shown in figure 3.

A line in figure 3 connecting the deposition velocities of the sands and the cobbles proves to be remarkably similar to Nevin's curve for settling velocities of coarse material (1946), which appears as curve number 3 in figure 3. The minimum impact of water necessary to sustain the motion of a grain, therefore, is just equal to the minimum vertical impact necessary to overcome its free fall in water. Fine sediments do not behave like coarse ones in this respect. With a decrease in the grain size, the settling velocity of fine sediments rapidly diminishes, although the velocity at which the bedload is deposited remains almost constant. As a consequence, silt and clay on

the bed of a slow-moving stream may be motionless at the same time that silt and clay are moved in suspension within the stream. The effect probably is due to the laminar boundary layer (Rubey, 1938) which shields the bed-load from the full impact of the current. The velocity of the water in contact with a grain decreases with increase in the thickness of the laminar boundary layer relative to the grain diameter. As a result, the mean velocity of the stream is far greater than the velocity which sustains motion of the bed-load, so the sustaining velocity at the bed may be closer to the settling velocity than to the mean velocity.

CURRENT RIPPLES

General

Current ripples (ripple-mark) have been observed by everyone who experiments with sands in a flume. They are groups of small dune-shaped mounds, transverse to the current, with the steep slope on the downstream side. The cause of ripples has been the subject of much speculation, but it is of only incidental interest in the present study of the current velocities at which they are formed and destroyed. The general relations between current velocity and ripples appear in figure 4. Current ripples seem to occur only when the flow is tranquil (synonymous with sub-critical or streaming). If the flow is torrential (super-critical, shooting, rapid) movement of bed material is in the form of antidunes or in smooth transportation. The flow characteristic described by "tranquil" and "torrential" is the response of the stream

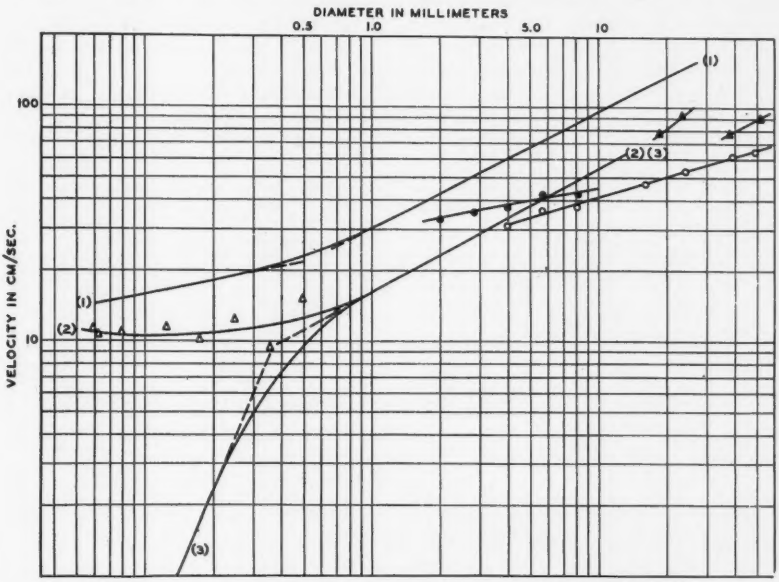

FIG. 3.—Velocity at which all motion of bed-load ceases. (1) Competence. (2) Motion ceases. (3) Settling velocity. Settling velocity and the velocity at which motion ceases are the same for grains larger than one millimeter. The circles represent observations by the U. S. Waterways Experiment Station (1935 b); open circles indicate that the bed slope of the flume was 0.002, solid circles that it was 0.0005. The open triangles show observations taken in a flume with a slope of 0.002, and the solid triangles are observations made in a tidal sluiceway at Sippowisset Beach (Menard, 1949).

to a change in energy. If the energy of a tranquil stream is augmented, the stream becomes deeper; but a stream with torrential flow becomes shallower if its energy is increased. Reverse depth relations obtain if the energy is decreased. A quantitative measure of this flow characteristic may be obtained from the Froude number (Rouse, 1938).

$$F=\frac{V^2}{gy}$$

V = mean velocity in cm/sec
g = gravity in cm/sec^2
y = depth in cm

The flow is tranquil if the Froude number is less than one; it is torrential if greater than one; the velocity at which F equals one is called "critical." The significant feature in the equation for the Froude number is that the critical velocity depends on the depth.

A comparison of the unique current ripples of Camas Prairie (Pardee, 1942) and the current ripples formed in Gilbert's flume (1914) indicates that the type of flow, rather than the mean current velocity, determines whether a stream bed is covered with ripples. The "ripples" of Camas Prairie apparently were formed by mighty currents generated by the failure of an ice wall which dammed Pleistocene Lake Missoula. They are 0.3 to 15 meters in amplitude, a few to 150 meters in wavelength, and are as much as 800 meters wide. The ripples are made up of gravel with particles varying from eight to 20 mm in diameter. Sections through the ripples show foreset bedding, and the general shape indicates that they are true current ripples of gigantic size. Gilbert's ripples were of the order of magnitude of millimeters in amplitude and centimeters in wavelength. The critical velocity in the experiments was usually about 100 cm/sec, and the ripples were destroyed when the current velocity approximated that value.

A shallow current would require a velocity of 140 cm/sec in order to move a 20 mm grain (Menard, 1949). The current in Lake Missoula, however, probably was more than 30 meters deep (twice the maximum amplitude of the ripples) so the competent velocity for 20 mm grains may have been somewhat different. Assuming for the moment that the velocity

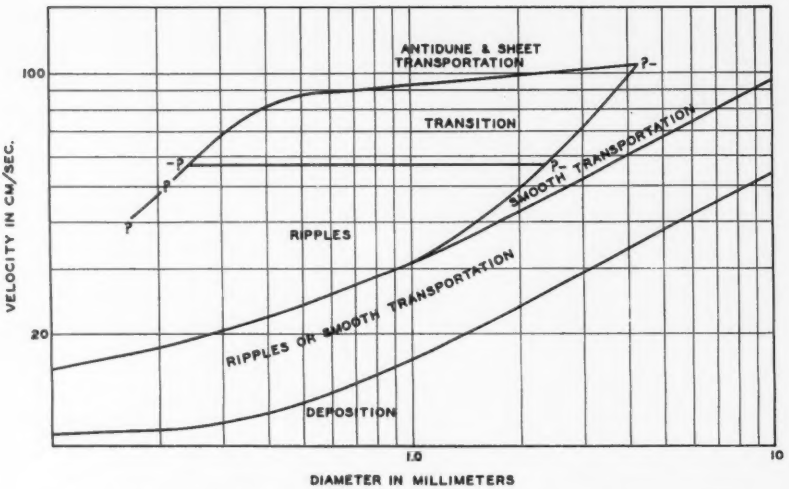

FIG. 4.—Generalized bottom conditions in relation to grain size and mean current velocity. Compare with figure 1.

required to move the largest grain was 140 cm/sec, and that this velocity was exceeded in Lake Missoula, the question arises as to why the ripples were not destroyed as they were by a slower current in Gilbert's experiments. The equation for the Froude number, however, indicates that the flow over Camas Prairie was tranquil if the current was no faster than this minimum velocity; moreover, with a depth of 3000 cm, the flow would have been tranquil at any velocity less than about 1700 cm/sec.

From the foregoing discussion, it is apparent that the depth of the flow is very important in determining whether a bed of grains of a given size will form ripples when acted upon by a current of a given velocity. It should be remembered while reading the succeeding sections of this paper that the data relating to the destruction of ripples and to other phenomena are quantitatively correct only if the flow is shallow, as it is in laboratory flumes.

Formation of Sand Ripples

Gilbert (1914) observed that a fine sand becomes rippled if only a few grains are moving. Chang (1939) and the present writer also have found that the velocity at which ripples are formed is the same as the competent velocity of the bed material. Even if only a few isolated sand grains in the flume are moving, in time they will form regular clumps. The current directly downstream from a clump impinges on the bed and causes a scour which forms a ripple. Sand movement becomes more rapid after the clumps are produced, and the last few ripples on a bed are formed much more quickly than the first ones.

Some investigators have seen sand moving in a smooth mode of transportation before ripples are formed. Smooth transportation does not apply to small grains, but it may be of some importance for those larger than one half a millimeter. For example, the Waterways' Experiment Station Sand 9 (grain diameter 4.08 mm) was moved by a velocity of about fifty cm/sec but it did not become rippled even at the maximum test velocity of seventy cm/sec (USWES, 1935a). Gilbert's data show that Sand C (3.17 mm) began to move in a smooth phase when the velocity was 61.6 cm/sec yet was not rippled until the velocity was 78.8 cm/sec. His Sand G (4.94 mm) did not become rippled even at a velocity of 104.6 cm/sec. For this reason, figure 4 shows that grains larger than about four mm do not ripple in shallow water.

TABLE 1.—*Influence of slope on the current velocity at which ripples are formed*
(Data from Liu, 1937)

Grain diameter mm	Slope	Competent velocity cm/sec	Velocity at which ripples formed cm/sec
3.4	0.0015	53.0	Was not reached in the test
	0.002	53.0	64.6
	0.005	57.3	62.2
	0.01	48.5	50.9
2.3	0.0017	46.3	Was not reached in the test
	0.0025	46.0	61.6
	0.005	47.2	53.6
	0.01	42.7	42.7

Liu (1937) measured the current velocities at which motion begins and also at which ripples are formed on monodisperse sands with mean grain diameters of from 1.4 to 4.4 mm. The selected data shown in table 1 suggest that bed transportation in the form of ripples may be characteristic of steep slopes. Apparently the rippling velocity for grains of 1.4–4.4 mm size is an inverse function of the slope, and is about the same as the competent velocity if the slope is as great as 0.01. This relation is substantiated qualitatively by other experiments (Casey, 1935) which indicate that a sand with a mean diameter of 1.32 mm will be rippled at the competent velocity if the slope is 0.005, yet will not be rippled if the slope is less.

The USWES data (1935a) suggest that there may be a similar slope-

velocity relation for ripple formation in finer grains. However, the present writer's tests with a bed slope of 0.002 show competent and rippling velocity to be equal; and so do Chang's experiments (1939), although he used a horizontal bed (the water surface, of course, had some slope).

Destruction of Sand Ripples

Suspension occurs if a current of water in equilibrium with a rippled bed begins to accelerate; with further acceleration the ripples are destroyed. The slowest velocity which produces suspension is important in sedimentology because only the finer grains are carried away, and the coarser remain as rippled bed-load. This velocity was measured in the present tests for all grain sizes from 0.062 to 0.5 mm (fig. 2); but it should be noted that suspension took place on ripple crests, not on a flat bed. Weak suspension from ripples began at velocities only a few centimeters per second faster than competent velocities on a smooth bed in all instances in which it was observed.

The current velocity at which ripples are destroyed is difficult to establish because observations of this phenomenon are not common. Some measure of the value may be obtained from Gilbert's data by noting the highest velocity at which he found ripples to exist. Although in many other experiments the maximum velocity obtainable is insufficient to destroy ripples, Gilbert's equipment could do so; therefore, the highest velocity at which ripples exist may be considered as but little less than the velocity at which they are swept flat and destroyed.

The fastest current velocity at which ripples can exist on material of a given grain size in shallow water is shown in figure 1, and in a generalized way in figure 4. The velocity appears to be of little importance in the destruction of ripples consisting of grains larger than 0.5 mm. Gilbert (1914) observed that sand grains in suspension (saltation), and the water in which they are suspended, form a layer which is denser and moves slower than the water which lies above. It may be that this layer so shields the ripples from the impact of the current that the mean velocity is of little significance.

Ripples are not to be expected if the flow is torrential, but Gilbert's data show that they do exist at Froude numbers between one and 1.33. Most of the tests at high velocities had a duration of only a few minutes so equilibrium may not have been established. Had the individual tests lasted longer, the ripples might have been destroyed when the Froude number reached one in each of the series of tests. Moreover the layer of suspended grains directly above the bed lowers the effective velocity and thus the Froude number of the layer. For these reasons, it appears possible that ripples are destroyed when the flow changes from tranquil to torrential at the bed.

Ripples are seldom found in well-sorted, coarse material, and figure 4 suggests the reason. The competent-velocity and ripple-destruction lines tend to intersect as the grain diameter increases, therefore, the range of velocities in which ripples can form and endure becomes limited.

Rate of Ripple Movement

Chang (1939) has determined experimentally that the ripple velocity is directly proportional to the mean velocity of a current. Transformed into metric units, his equation is

$$Vr = 1.32 \cdot 10^{-10} V^5$$

Vr = velocity of ripples

V = mean velocity of current

Due to scattering in the original data, however, the coefficient may be too large or too small by ten per cent. The maximum current velocity at which ripples can exist in shallow water is about 100 cm/sec, so the maximum velocity of the ripples is about 1.5 cm/sec.

ANTIDUNE AND SHEET BED MOVEMENT

Bed-load transportation occurs in

either a smooth sheetlike phase or in antidunes if a stream is moving too fast for the bed to be rippled. "Antidune" refers only to low, symmetrical, fast-moving sand waves which migrate upstream, but the expression "smooth transportation" is ambiguous because it is used to identify the motion of bed-load when the current velocity is only slightly faster than the competent velocity, and also to indicate the rapid movement of a sheet of material when the current velocity is much faster and the flow is torrential. This usage is comparable to calling both ripples and antidunes by the general term "sand waves" instead of distinguishing between the two. In order to separate the different modes of smooth transportation, it is suggested that "smooth transportation" be confined to the minor movement of the bed during tranquil flow, and "sheet transportation" be used to indicate the rapid sheetlike motion of the sand bed when the flow is torrential.

Gilbert (1914) noted that the sheet form always preceded the antidune in his experiments. This observation has led to a common misconception that the sheet phase is associated with slower current velocities, and the antidune phase with faster ones. Gilbert's procedure was not to increase the velocity or slope or depth in any systematic fashion, but to vary the water discharge and the sediment load. The sand added to the flume assumed a stable slope and then measurements were taken of depth, slope, velocity, etc. Table 2 shows some typical data in which similar velocities have been paired for comparison of the two modes of transportation. Maximum and minimum velocities for sheet and antidune transportation are shown in figure 1. Clearly the velocity does not determine which form will occur. Gilbert has suggested that the proportion of the velocity to the depth or the load is critical. Nevin (1946), on the other hand, considers antidunes to be scours which tend to form when the stream slope is too steep to be in equilibrium with the load and velocity. The data in table 2 substantiates this concept; in every pair of similar velocities, antidunes occur on much steeper slopes than does the sheet mode of transportation.

Langbein (1942) has analyzed Gilbert's data and finds that antidunes are not formed unless the flow is torrential. The fluid viscosity also affects antidunes, so that an increase in viscosity causes them to form at a Froude number closer to one. However, sheet transportation, also, occurs only if there is torrential flow, so the type of flow does not explain why sediment moves in a smooth sheet or in antidunes.

Bagnold (1941) emphasizes the role of saltation as an important mode of transportation of sand in air. A saltating grain bounces along or by impact dislodges another which is propelled into the air. This bouncing or dislodging phenomenon seldom has been observed under water. Although grains frequently leave the

TABLE 2.—*Occurrence of two modes of transportation at similar velocities*
(Data from Gilbert, 1914)

Grain diameter mm	Depth cm	Slope	Velocity cm/sec	Bed movement gms/sec/cm	Mode of transportation
0.305	3.84	0.0069	66.7	0.89	sheet
	1.86	0.0137	68.9	1.69	antidune
	5.55	0.0063	95.6	3.70	sheet
	2.71	0.0143	94.2	4.40	antidune
0.506	4.66	0.0152	82.4	3.80	sheet
	1.71	0.0210	75.0	3.13	antidune
	6.00	0.0120	131.6	8.88	sheet
	1.89	0.0224	135.6	5.62	antidune

bed by saltation, they rarely rebound when they settle back to the bed. The difference in saltation of sand in air and water is explained by Kalinske (1942) on the basis of the resistance of a grain to movement in a medium with laminar flow. For the same shear, the resistance depends on the density of the medium. Hence the rebound of a grain in water should be about 1/800 of the amount in air. At velocities adequate to produce any appreciable saltation in water, Kalinske concludes that flow would be turbulent and any grain detached from the bed would move in suspension. Whether saltation occurs at all under water is a matter of definition. "Saltation" refers to a leap or jump, and grains have been seen to leap from the bed in a flume (Gilbert, 1914); on the other hand, grains do not rebound or make a series of leaps, so it may be more reasonable to consider the initial "leap" as a pull caused by turbulence. The observed high concentration of suspended sediment near the bed may be thought to result from saltating grains which leap only a certain distance from the bed, or it may be considered as due to the vertical gradient in the concentration of suspended material which is expressed by the Austausch coefficient (Hjulstrom, 1935) or, as it is otherwise known, the eddy viscosity (Inman, 1949).

IMPORTANCE OF THE VARIOUS TYPES OF BED-LOAD MOVEMENT IN NATURAL CURRENTS

The sedimentary processes observed in flumes are not so different from those in small natural streams, so the velocity-size relations shown in figure 4 may be assumed to be valid. The greater depth and turbulence of large rivers make a comparison more difficult. However, there seem to be ample data to indicate some features of bed-load transportation under most circumstances.

Many of the large rivers of the earth have mean velocities of about one-and-one-half meters per second in normal flow, and four to five meters per second during floods (Lapparent, 1900). The flow is torrential only during some floods. Therefore antidunes and the sheet phase of transportation seldom occur and the bed-load moves in ripples or the smooth phase. In the Mississippi River below Cairo, Illinois, almost all the bed-load consists of sand ranging in size from 0.1 to 1.0 mm (USWES, 1935a). These are precisely the sizes which invariably form ripples in flumes. It appears likely that much of the bed-load of large rivers moves in ripples. The mean velocity, however, frequently exceeds the minimum velocity for weak suspension, and the finer sizes should move at a faster rate than the larger ones which do not leave the bed.

This discussion is not meant to imply that most sediment moves to the sea in the form of ripples. The mere existence of ripples suggests that erosion is nearly balanced by deposition, and that only a thin, superficial layer of the bed is in motion. Transportation of bed-load during floods is of a different order of magnitude if one may judge by the deepening of the channel or the thickness of the sediment in motion. Antidunes 1.8 meters high have been observed in the San Juan River (Pierce, 1916); and progressive sand waves—large, irregular waves of sediment observed in fast, silt-laden rivers—5.65 meters high were found in the Mississippi River (Hider, 1883). Therefore, not just a thin surface layer, but bed-load several meters thick may be moved as sand waves in rivers in flood.

Ripple transportation may be more important in the open ocean where the current velocity is seldom very fast. Shepard (1948) reports bottom velocities of 36.7 cm/sec in 160 fathoms on the California continental borderland, and 14.6 cm/sec in 1050 fathoms in the Santa Cruz basin. These velocities may move sediment in ripples, but they are far too slow to form antidunes or progressive sand waves.

On the other hand, tidal estuaries and channels are among the most favorable

locations for sand waves. A surface velocity of twelve knots occurs in the Seymour Narrows between Vancouver and the mainland (Shepard, 1948), and surface currents of several knots are common elsewhere. Stetson (personal communication) has observed bottom velocities as high as 3.4 knots in Vineyard Sound. In these circumstances, progressive sand waves and possibly antidunes are formed, and transportation by ripples probably is of negligible importance, although the bottom may be rippled most of the time when the velocity is small due to the stage of the tide.

CONCLUSION

The quantitative relations between grain size, bottom conditions and mean current velocity in shallow water are depicted in figure 4. Competent velocity, however, is known to be affected by turbulence, thickness of the boundary layer, depth, slope, and the density, shape, and sorting of the bed material. All these factors may also influence other sedimentary phenomena in addition to the initial movement of the bed. Nevertheless the *qualitative* relations shown in figure 4 should apply to all sedimentary and hydraulic conditions, and the following conclusions may be drawn:

1. Sand grains can be moved by a slower current if the bed is rippled than if it is smooth, but the difference amounts to only a few centimeters per second.

2. Ripples usually are formed if fine grained sands move at all; yet, if the grains are coarser, the rippling velocity may be larger than the competent velocity. In the latter instance, the movement of sediment at low velocities occurs in a smooth phase.

3. Steep slopes favor the formation of ripples.

4. Ripples are destroyed at a current velocity which probably corresponds to a change in the nature of the flow from tranquil to torrential. The greater the water depth, therefore, the greater the current velocity required to destroy ripples.

5. Antidunes and sheet transportation occur only if the flow is torrential.

6. Bed-load of any size larger than silt ceases to move at about two-thirds of the competent velocity. This corresponds to the settling velocity of grains larger than one millimeter, however it is much larger than the settling velocity of smaller grains.

The conclusions stated above are based on tests in flumes in which both the sediment movement and the water movement could be observed. The field geologist interested in paleoecology or paleogeography can see only half of this picture—the sediments which once were moved. The flume observations may provide clues whereby the sediments, now rocks, will reveal the characteristics of ancient currents.

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FIGS. 1–5, SEPTEMBER, 1950

THE EFFECT OF CONTINUOUS ADDITION OF MINERAL GRAINS TO A SETTLING ENVIRONMENT

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ABSTRACT

A method was designed to observe the settling behavior of mineral grains under conditions of continuous addition of grains to a fluid medium. This was accomplished in a modified elutriator in which the grains were held in "teeter" by ascending currents of water, even though a flow of additional grains constantly entered the suspension. The relations between size, shape and density of grains, and the relation of particle density to pulp-density were determined.

INTRODUCTION

In a study of the settling of sediments, environments are commonly encountered which do not conform with the ideal condition required by the laws of Stokes, Newton, Rittinger, and others. Settling conditions are complicated by the presence of many particles which interfere with each other during their fall, by deviation of particle shape from the ideal sphere, by an increase of density and apparent viscosity of the mixed solid-liquid system, and by other factors that are not easily defined. Particles less than 50 microns in diameter follow closely Stokes' law for viscous conditions; whereas, coarser particles (1 mm and larger) are supposed to follow Newton's law for turbulent conditions. Particles of intermediate size (50 microns to 1 mm) may follow still another law that is not easily formulated, due to the fact that no sharp boundary exists between streamline and turbulent flow.

This study was designed primarily to develop techniques for the beneficiation of low grade ores, but it involved the behavior of mineral grains of the intermediate size range between turbulent and viscous settling environments. Consequently, data were assembled that have a bearing on the transportation and sorting of sediments in environments where heavy, heterogeneous, suspended loads are being deposited.

Richards' (1907) experimental work with quartz and galena demonstrated that the diameter of the settling particle determined the law of settling it would follow. Rubey (1933), Wadell (1933), Oseen (1913), and Goldstein (1929) have worked on the problems of the intermediate zone with varying degrees of success, and more recent studies by Taggart (1945) claim to provide the desired continuity and to tie the three regions of settling into one law that is based on Castleman's function.

The deposition of sediments containing a mixture of mineral grains of different specific gravity, both heavy and light, has been analyzed by Rittenhouse (1943) in terms of hydraulic equivalents. His results are of value in determining the relative densities of the heavy minerals commonly found in sediments. Krumbein (1942) has reported observations on the influence of the shape of settling particles, but his experiments involved "free fall" settling in quiet water in one instance and a limited amount of sediment transported in a flume, in the other. His results present the relation between the Froude and Castleman functions where no heavy load of sediment is involved.

When the settling medium becomes heterogeneous, due to the increasing number of particles in suspension, it no longer behaves as a two-phase system consisting of a homogeneous fluid as one

component and dispersed solid particles as the second. It is rather a single mixed system of fluid and solids. Likewise, a column of water in which mineral particles are settling, or the converse case where particles are held in suspension by a rising current of water, is also a suspension system and the settling rate of a given particle in such a system will be influenced not only by the viscosity of the water component, but by the viscosity of the mixed system.

Einstein (1920) investigated the problem of suspensions and derived an equation for the apparent viscosity of a dilute suspension. His equation is

$$n_a = \frac{n}{1-2.5y}$$

Where

n_a = apparent viscosity of suspension
n = viscosity of fluid
y = volumetric fraction of suspension occupied by solids.

This equation was used by the writers for calculating the apparent viscosity in the sorting column.

The effect of shape of particles on the apparent viscosity of a suspension or pulp was investigated by DeVaney and Shelton (1940). They found that suspensions of equal density but made of differently shaped particles exhibited different viscosities. In a moving suspension, rounded grains slip and roll past each other, whereas angular and irregular grains tend to wedge and interlock. Thus the apparent viscosity of a suspension of rounded particles is lower than that of a suspension composed of angular grains.

Under Stokes' law the buoyant force acting on a particle is equal to the weight of the displaced fluid medium, and the effective downward force on the particle is proportional to the difference in density between the particle and the fluid, i.e., $\Delta - d$, where Δ is the density of the particle and d is the density of the fluid. However, in a suspension of mineral particles, the buoyant force on any given particle is not simply the force of the weight of water displaced. It is rather the weight of the suspension medium displaced and this has a density that is the average of the suspension and not that of the water component alone. Thus as the density of the suspension increases, the buoyant force on a given particle increases also.

When a large number of particles settle in a fluid with limited boundaries and the number per unit space is so great that individual particles bump and jostle each other and interfere with downward motion, then the rates and behavior of settling do not follow any well known law. Monroe studied such "hindered settling" phenomena experimentally and tried to show that a boundary exerted a real influence whether the boundary was that of the wall of a vessel or that of a moving particle. Furthermore, when many particles are settling, the fluid displaced by a number of adjacent particles, must move around and up between and through the interstitial spaces of the particles. As the suspension increases in density, the velocity of the fluid moving through the interstice increases and eventually interstitial currents are developed.

Since so many variable factors are involved in settling from moving suspensions, the following experiments were conducted in an attempt to determine if any could be evaluated.

EXPERIMENTAL OBSERVATIONS

The experimental procedure employed by the writers was somewhat different from that used by previous investigators who have reported observations on both "free-fall" and "hindered" settling. In this study new mineral grains differing in size, shape and density were constantly added to a settling environment in which the grains were held in "teeter" by ascending currents of water. Observations were recorded on (1) the effect of the rate of feed on settling, (2) the density of the suspension in the teeter zone, (3) the relation between diameters and densities of particles, (4) the relation be

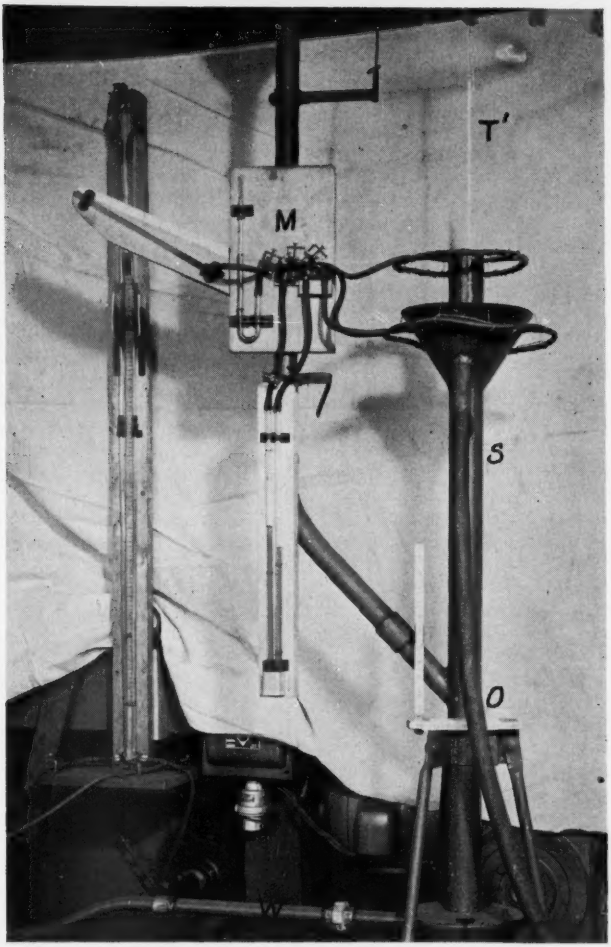

FIG. 1.—Photograph showing construction of Constant Feed Classifier. F, feed funnel connected with Dorr Classifier above (not shown); S, sorting column; O, overflow to settling tank (not shown); M, manometer tubes; T, funnel to trap below (not shown); T′, thermometer; W, water intake. Scale indicated by partly folded measuring rule.

tween particle density and suspension density, (5) the influence of the shape of particles on settling characteristics, and (6) the plausibility of plotting results in terms of Castleman and Reynolds functions.

An apparatus was constructed in which a suspension in dynamic equilibrium was created and maintained, even through a flow of additional mineral grains constantly entered the suspension. The apparatus consists of a sorting column that

permits the discharge of mineral grains of low settling rate through an overflow and a trap for mineral grains of high settling rate at the lower end of the column. It is a modified elutriator here referred to as a Constant Feed Classifier (fig. 1), in which the suspension consists of three classes of particles: (a) slow settling grains that are discharged in the overflow, (b) rapidly settling grains which settle against the upward moving current of water and are trapped at the lower end of the column, and (c) grains, the settling rate of which is equal to the rising pulp velocity and thus remain in the column in a state of agitated suspension known as "teeter."

Even though new mineral grains are constantly fed into the sorting column, they do not accumulate to clog the column, for as the grains in teeter accumulate, the pulp density of the suspension in the teeter zone increases. This increase of density simultaneously increases the buoyant force of the suspension on the teeter grains, and thereby lowers the settling rate of the grains and forces them to move upwards, out of the teeter zone to the discharge. Thus, the discharge contains both the slow-settling grains and the grains held in teeter. The former were washed from the grains in teeter in a simple elutriator not designed for the constant feeding of new mineral grains. Since the isolated teeter grains differ in size, density, and mineral composition, they were screened, weighed and average density determinations were made.

The sample used for experimental purposes was a mixture of quartz, ferruginous chert and hematite. It was taken from tailings of an iron ore concentration operation that used a Dorr Duplex Classifier. The reason for using the mixture was the fact that it had been subjected to washing, to solvents and to attrition in the concentrator and, therefore, the mineral particles were stable and did not disintegrate appreciably during the elutriating process.

A small double-rake Dorr Classifier was added to the flow circuit to regulate the rate of feed, to wet the mineral grains and to remove air bubbles and dust that might adhere to them. The wetted and washed grains were then discharged into the end hopper of the classifier and from there a small stream of water sluiced them into the feed funnel of the elutriator. (See fig. 1.)

Four experimental runs were made with mineral grains from a large, thoroughly-mixed, stock sample. Each run was given a different rate of feed and for each run, the velocity of the water was adjusted to give a suspension of maximum pulp density in the sorting column for that particular rate of feed. The pulp density was determined by readings on both static and differential manometer tubes and the temperature was read from a thermometer hung in the top of the sorting column.

In order to permit an experimental check on consistency of operation of the equipment and to check the possibility of reproducibility of results, three samples were taken from each run, and each sample was processed and studied separately but identically. Observations were made also of actual volume of water and solids in the sorting column; for later calculations such as a determination of the rising velocity in the sorting column, the per cent volume of suspension occupied by solids, and the average density of the pulp or suspension of mineral particles. (See table 2.)

TABLE 1.—*Size distribution of mineral grains in sample before sorting in Constant Feed Classifier*

Mesh No.	Openings in mm	Percentage by weight
28	.589	Tr.
35	.417	16.2
48	.295	24.3
65	.208	21.5
100	.147	17.5
−100	−.147	20.5

The size distribution of the mineral

grains in the sample that was passed through the classifier is shown in table 1. Closer sizing was done on the teeter grains that were separated from the sample in order to segregate them into closely related size groups. As is indicated in table 3, the grains that passed the 100 mesh sieve were washed out in the second elutriator.

When the logarithm of the ratio of average density to the diameter of mineral particles (table 5) is plotted against the logarithm of the diameter, a nearly straight line curve results. Log-log plots

TABLE 2.—*Results of four runs of mineral sample through Constant Feed Classifier*

Run No.	Dry wt. solids, lbs.	Wt. water in lbs.	Velocity pulp ft./sec.	Density of pulp	% Vol. solids in pulp
1	67.28	93.14	.645	1.436	16.87
2	47.66	90.50	.598	1.337	12.97
3	42.40	127.36	.401	1.248	8.59
4	12.56	128.18	.379	1.082	2.72

TABLE 3.—*Size distribution of teeter grains*

Mesh No.	Calc. av. diam. mm	Percentage by weight			
		Run 1	Run 2	Run 3	Run 4
14	1.282	0.09	0.13		
16	1.079	0.18	0.28		
20	0.912	0.35	0.53	0.12	
24	0.767	0.57	0.76	0.18	
28	0.645	1.89	2.20	1.33	0.61
32	0.542	27.38	28.88	24.63	12.51
35	0.456	36.70	35.58	34.57	22.54
42	0.384	19.68	19.99	23.34	28.16
48	0.323	9.82	8.90	11.34	21.98
60	0.270	2.79	2.34	3.73	10.58
65	0.227	0.45	0.27	0.63	2.60
80		0.04	0.03	0.13	0.33
−80		0.06	0.07		0.25
Calc. av. diam. mm		0.455	0.461	0.440	0.392

TABLE 4.—*Average density of mineral grains held in teeter*

Mesh No.	Av. diam. in mm	Run 1	Run 2	Run 3	Run 4
14	1.282	3.706	3.558		
16	1.079	3.793	3.698		
20	0.912	3.906	3.852	3.563	
24	0.767	4.036	3.964	3.880	
28	0.645	4.230	4.204	4.155	3.701
32	0.542	4.401	4.415	4.314	3.954
35	0.456	4.525	4.534	4.467	4.172
42	0.384	4.657	4.671	4.620	4.383
48	0.323	4.746	4.751	4.727	4.578
60	0.270	4.816	4.835	4.792	4.713
65	0.227	4.796	4.815	4.839	4.773
80	0.191	4.649	4.888	—	4.807

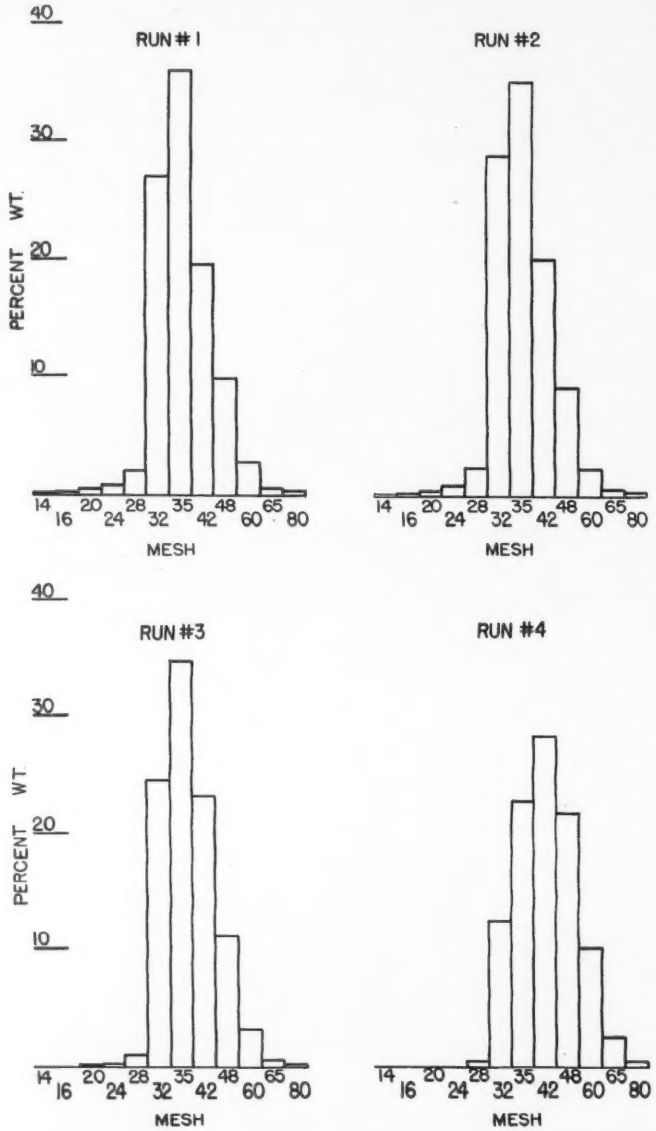

FIG. 2.—Histograms showing size distribution of mineral grains held in teeter during sorting in the Constant Feed Classifier.

TABLE 5.—*Ratio of average density of disaggregated teeter grains to average diameter of mineral grains* (ρ/d)

Mesh No.	Run 1	Run 2	Run 3	Run 4
14	2.89	2.78		
16	3.52	3.43		
20	4.28	4.22	3.91	
24	5.26	5.17	5.06	
28	6.56	6.52	6.44	5.74
32	8.12	8.15	7.96	7.30
35	9.92	9.94	9.80	9.15
42	12.13	12.16	12.05	11.41
48	14.69	14.71	14.63	14.17
60	17.80	17.87	17.72	17.42
65	21.13	21.21	21.32	21.03
80	24.40	25.66	—	25.23

of the ρ/d ratio against diameter gave curves nearly parallel to each other, but with a slight tendency to converge in the direction of greatest particle density. Such curves would permit the determination of particle densities by drawing the ρ/d curve and picking off the density of particles whose density had not been determined experimentally. Furthermore, the curves can be used to predict the diameter of particles of known densities which differ from the densities of the teeter particles in a suspension.

RELATION OF DENSITY OF MINERAL GRAINS TO PULP DENSITY

There is a significant difference between the results obtained with the Constant Feed Classifier used by the writers and the "hindered settling" experiments reported by Monroe and Richards. In the former, many kinds of mineral grains are constantly fed into the sorting column where they co-mingle with the teeter particles already in the teeter zone, whereas Monroe and Richards added only one charge of mineral grains and allowed it adequate time to be sorted in a rising column of water. In the Constant Feed Classifier, fine and slow-settling mineral grains and water flow up through the interstitial spaces between

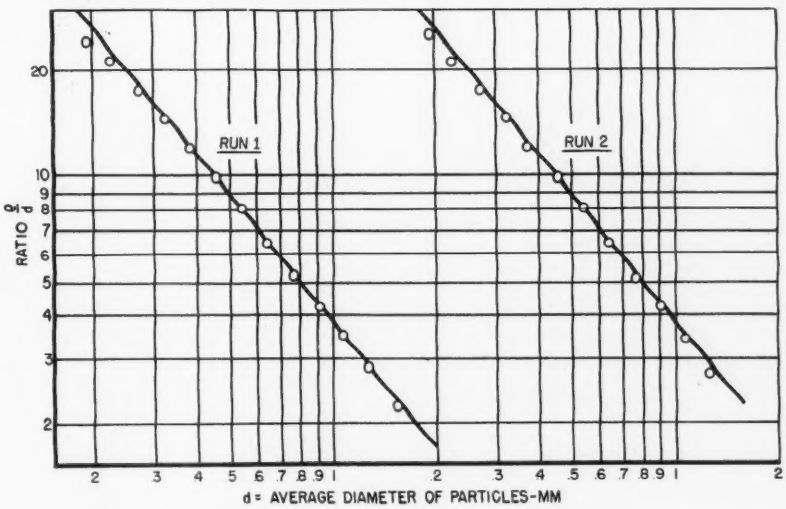

FIG. 3.—Log-log graphs of the average diameter plotted against the ratio of the density to the diameter of the mineral grains.

the mineral grains already in teeter in the sorting column, but in the "hindered settling" experiments referred to above, only clear water flowed through the interstitial spaces. From his experiments, Monroe (1889) concluded that "spheres moving en masse will * * * require to support or lift them, a rising current of but one-sixth the velocity to support or lift a single isolated sphere of the same material."

When the density of the mineral grains of the various screen sizes is plotted against the density of the pulp in the teeter zone, the curves show a shift in particle density with pulp density. It is thus evident that for mineral grains of a given size, a suspension load of high density will support particles of high density and vice versa. Similarly when the density of the teeter particles by screen size is plotted against the velocity of the rising pulp in the column, curves are obtained which show that as the pulp density is increased, a higher velocity is required to maintain higher density grains of a given size in teeter. These observations do not conform with Monroe's statement quoted above.

CASTLEMAN AND REYNOLDS FUNCTIONS APPLIED TO THE SETTLING PROBLEM

The Stokes and Newton-Rittinger laws of settling are valid only for particles in a free-settling environment and the points of transition between the two are not definite. Where a mixture of mineral grains is settling in an unstable environment, the size of some grains would place them in the turbulent settling region of one law, and other grains would be of the size to place them in the intermediate region. Where both small and large grains are simultaneously comingled in the same unstable settling environment, both may be subject to the same settling law.

To provide a uniform and equitable basis of comparison for experimental data, the writers used the Castleman and Reynolds functions to avoid the necessity of deciding the position of the transition point between the laws of Stokes and Newton.

Castleman's function is

$$T=\frac{2}{3}g\ \frac{d^3}{n^2}\delta(\Delta-\delta)$$

where

g = acceleration of gravity
d = diameter of particle
n = viscosity of pulp
δ = density of pulp
Δ = density of particle

Reynolds' number is $N=dv\delta/n$

where

d = diameter of particle
v = velocity of particle
δ = density of pulp
n = viscosity of pulp

TABLE 6.—*The Reynolds (N) and Castleman (T) functions for the teeter grains run no. 1*[1]

Screen mesh No.	Reynolds	Castleman
16	120.0	4289
20	101.0	2683
24	85.1	1683
28	71.5	1079
32	60.1	676
35	50.6	419.9
42	42.6	261.7
48	35.8	160.1
60	30.0	96.4
65	25.2	56.8

[1] Similar values were calculated for runs 2, 3, and 4.

The values of the Castleman and Reynolds functions by screen sizes of the mineral grains in the teeter zone are given in table 6. These values are plotted on a log-log chart in figure 4. The curves are straight lines that are nearly parallel, with slope angles of 20° to 22°, and they lie for the most part above the standard curve representing free-fall settling conditions. The curves for runs of different pulp density are displaced from one another in regular order and the curves representing the higher pulp densities are displaced farthest from, and the curves representing lowest pulp densities are closest to the standard free-fall curve.

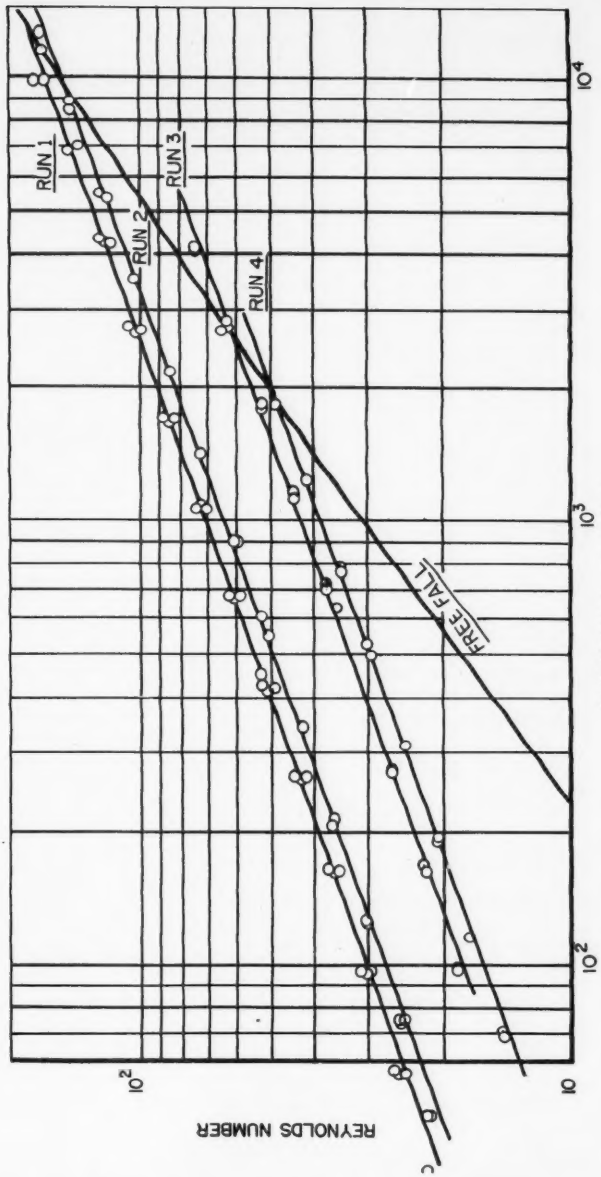

FIG. 4.—Log-log graphs showing the values of Castleman's Function plotted against the Reynolds number for the mineral grains held in teeter in the Constant Feed Classifier.

The experimental curves lie well below the position of the Newton-Rittinger zone, but because of that parallelism, they might indicate turbulent conditions of settling even for particles whose diameters would obviously place them in the intermediate size zone of settling. For a given run with the experimental sample, the factors of gravity (g), viscosity (n), pulp density (δ) and velocity (v) are constant. The only variables are the density and the diameter of the mineral grains. The factor of diameter of the grains changes at a greater rate and over a greater range than the factor of grain density, the Reynolds' number (N) is proportional to the particle diameter (d), and the Castleman function (T) is proportional to d^3. For this reason the factor, d, in both equations (Reynolds' and Castleman's) strongly influences the slope of the curves.

INFLUENCE OF SHAPE OF MINERAL GRAINS ON RATE OF SETTLING

Flat, plate-like particles have lower settling rates than spherical mineral grains of the same density. The teeter grains separated from the sample by the Constant Feed Classifier varied widely in size, shape and density, but still all settled at the same rate. To check the relation between shape and density, the grains held on a given screen were re-screened on Ton-Cap screens that have rectangular openings and the density of the platy grains was determined. The percentage difference between the densities of the products retained on and those that passed through the Ton-Cap screens varied from a high of nearly 17 per cent to a low of less than 1 per cent. In the products of four runs through the Constant Feed Classifier, where rate of feed and velocity of flow were varied, the platy grains that passed through the Ton-Cap screens, showed a constant decrease in the percentage difference in density from a high in the coarsest sizes to a low in the finest particles.

If one compares the Ton-Cap fractions from a given square aperture screen size with others, a very definite trend is noted. For instance, when the grains on the 35 mesh standard sieve are re-screened in a Ton-Cap sieve, the percentage of platy particles passing through the rectangular openings ranges from 11 per cent in run 1′ to 27.2 per cent in run 4′. Likewise for the 42 mesh particles, the percentages range from 5 per cent to 19 per cent. These runs were made at progressively lower velocities of flow (see table 2) and the density of the pulp decreased from 1.61 to 1.08.

In using the Ton-Cap screens, a given sample from a standard screen was divided into two products only, one passing through the screen and the other retained on the screen. The least dimen-

TABLE 7.—*Relative densities of Ton-Cap screen fractions*[1]

Standard screen mesh	Ton-Cap products	Densities			
		Run 1′	Run 2′	Run 3′	Run 4′
24	+	4.025	3.898	3.449	
	−	4.053	3.971	3.886	
	diff.	0.028	0.073	0.417	
	% diff.	0.7	1.85	12.0	
35	+	4.536	4.538	4.359	3.437
	−	4.569	4.587	4.435	3.630
	diff.	0.033	0.055	0.076	0.193
	% diff.	0.73	1.21	1.73	5.62

[1] The densities of the fractions from the 20, 28, 32 and 42 mesh screens were determined also and gave similar results.

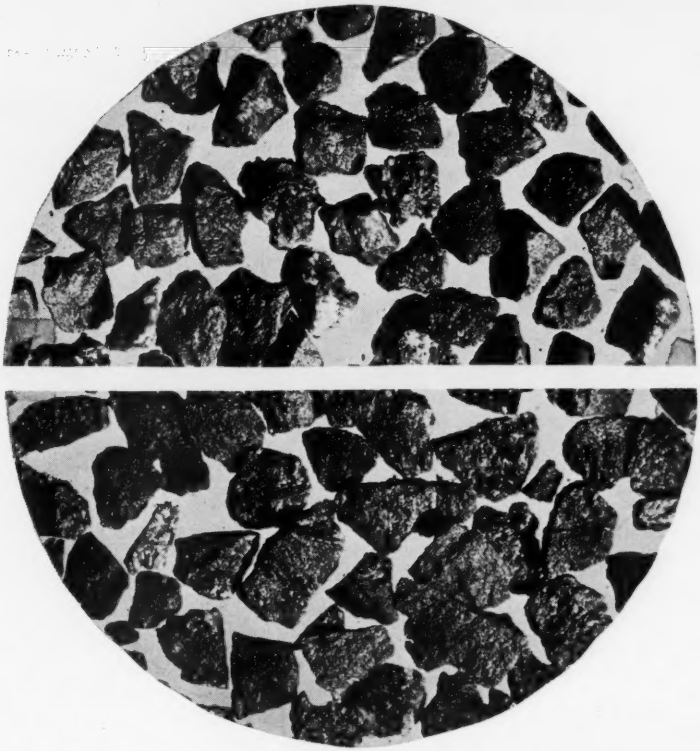

FIG. 5.—Photomicrographs of mineral grains used in experiment, showing: *above*, irregular shapes of grains that passed sieve with rectangular openings and *below*, flat-surfaced and platy grains that passed through Ton-Cap sieve with rectangular openings. ×10.

sions of flat particles passing through the openings of a given Ton-Cap screen vary from the full width of the narrow opening, down to a smaller value which cannot be determined accurately, but was estimated at about one-half the narrow dimension.[1] By taking the mean of these two values, full width and one-half full width, an average least dimension of flat particles may be determined. Calculations on the flat particles through all of the Ton-Cap screens were within 0.8 percent of 33 percent. This means that the average thickness or least dimension of the flat particle is about one-third of the width.

[1] This was estimated from a study of the shape of the grains involved. There were no thin, micaceous flakes.

CASTLEMAN AND REYNOLDS FUNCTIONS FOR PLATY MINERAL GRAINS

Both Castleman's and Reynolds' formulas contain the factor d, the diameter of the particle. For flat or platy particles the value d is not some simple dimension but rather a complex value that is a func-

tion of the shape of the particle. Wadell defines the size of irregular solids in terms of their "true nominal diameter" which is the diameter of a sphere of the same volume as the irregular solid.

The flat particles isolated in this study had an average thickness to width of 33 per cent. Since the individual particle is plate-like, it is roughly equivalent to a prism of dimensions $3a \times 3a \times a$, where "a" equals smallest dimension. A sphere, equal to the volume of such a prism can have both its radius and surface area determined. Twice the radius of the equivalent sphere will then be the true nominal diameter of the flat particle. The coefficient of sphericity (γ) can also be determined since it is the ratio of the surface of the sphere to the surface of the prism. The true nominal diameters for the flat fragments that passed through the Ton-Cap screen were calculated and these values were used to determine the Castleman and Reynolds functions for such particles.

When the Castleman and Reynolds functions (table 8) of the platy grains are plotted to the same scale as those of the other teeter particles from which they were screened, the curves are almost identical. This was expected, since the flat particles settled in the same environment in the sorting column. Since the settling rates were the same, the shape factor of the flat or platy particles must be compensated for by a greater particle density. This was verified experimentally. (See table 8.)

CONCLUSIONS

1.—The settling behavior of mineral grains under conditions of continuous addition of grains to the fluid medium was observed in a controlled laboratory environment. Concordance in the results with triplicate samples warrants the conclusion that the observations are valid under the conditions as described.

2.—The density of the suspension in the sorting column, calculated from manometer readings, was consistently greater than the density of the overflow suspension. This relationship indicates that mineral grains accumulated in the sorting column in a state of teeter.

3.—By plotting the log of the ratio of the average density to the diameter of the grains against the log of the diameter, a curve is obtained from which it can be calculated that the density of a mineral grain held in teeter is inversely proportional to the grain diameter to a small fractional exponent.

4.—The plotted values of Castleman and Reynolds functions by screen sizes of the mineral grains held in teeter, indicate turbulent conditions of settling even for particles the diameter of which would normally place them in the intermediate size zone between those that are supposed to follow Stokes' law for viscous conditions and those that follow

TABLE 8.—*Castleman and Reynolds functions of the platy grains that passed Ton-Cap screens*

Run No.	Calc. nom. diam. mm	Vel. cm/sec	Reynolds' No. (N)	Density of grains	Castleman's No. (T)
5	.781	15.27	50.8	4.121	876.9
	.657	Do.	42.7	4.153	507.9
	.552	Do.	35.9	4.325	334.8
	.464	Do.	30.1	4.991	247.7
	.390	Do.	25.4	4.569	129.0
	.329	Do.	21.4	4.785	82.9
8	.464	6.19	18.8	3.550	638
	.390	Do.	15.8	3.630	391
	.329	Do.	13.3	4.076	276

Newton's law for turbulent conditions.

5.—When calculated true nominal diameters of flat and platy mineral grains are used to obtain Castleman and Reynolds functions, the curves for the functions are almost identical with those obtained from the other mineral grains held in teeter. Since the flat grains settled in the same environment as the other grains, the shape factor of the platy grains is compensated for during settling by a greater density of the mineral grains.

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REMOVAL OF IRON OXIDE COATINGS FROM MINERAL GRAINS

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ABSTRACT

Hydrogen produced by the action of oxalic acid on aluminum is an effective agent for the removal of iron oxide coatings from mineral grains, and, because the method is rapid and simple, it is recommended for routine analysis of granular materials. Data are presented to compare the results obtained by this method with those produced by the use of various other reagents.

INTRODUCTION

The removal of surface coatings of iron oxide from mineral grains frequently is an important first step in the microscopic study of detrital materials or crushed mineral fragments. Standard petrographic references suggest boiling the grains in dilute hydrochloric acid to achieve this end, but although this procedure is effective in removing the coatings, it also attacks material that forms an integral part of many samples. The problem is to find a reagent which will remove deleterious material, but which will not adversely affect the mineral grains present in the sample. At the same time, the action of the reagent must be rapid and the procedure simple, so that the method may be applied easily to routine analysis.

Soil technologists have developed techniques for the removal of iron oxide, but since the information which the soil technologist seeks differs in many respects from that in which the geologist is interested, these techniques generally are too complicated and time-consuming for routine mineral studies. However, portions of the soil analysis procedures may be borrowed and adapted for use in the petrographic laboratory. Gilbert (1947, p. 85), realizing this possibility, investigated the petrographic application of various acids used in soil analysis, and found that digestion in 20 per cent phosphoric acid is an effective method of cleaning detrital grains and of disaggregating sandstones cemented by calcium carbonate. The results of the present investigation corroborate Gilbert's qualitative data, and in addition, indicate other methods of treatment suitable for petrographic studies.

METHODS

For the present study, mineral specimens of calcite, dolomite, and apatite were crushed and the fragments sized. Five-gram samples of the 250- to 1000-micron fraction of each, and a similar amount of shredded biotite, were boiled gently for five minutes in 50-cc each of 20 per cent citric acid, 20 per cent tartaric acid, 10 per cent oxalic acid, and 20 per cent phosphoric acid, to determine the effects of each of these acids on the crushed mineral samples. To learn the effectiveness of each acid in removing iron oxide, a quartz-sandstone, in which the individual quartz grains had a heavy coating of iron oxide, was crushed to free the component grains, the disaggregated material sized, and 5-gram samples of the 250- to 1000-micron size fraction tested in exactly the same manner as the mineral samples. In addition, 20-gram samples of each of the previously mentioned materials were boiled gently for 20 minutes in a 5 per cent solution of oxalic acid containing an aluminum cylinder; 10-gram samples of each material except biotite were boiled gently for 20 minutes in a 10 per cent solution of ammonium tartrate in contact with

aluminum; and a 10-gram sample of the sandstone was agitated intermittently for two hours in a 5 per cent solution of ammonium tartrate.

Jeffries (1941) has described a procedure for the reduction and solution of free iron oxide coating soil particles, by means of hydrogen produced by the action of oxalic acid on metallic aluminum. Since the quantitative determination of the amount of iron removed is not of importance to the petrographer, Jeffries' method was modified in the course of the present study. A 20-gram sample of the sized material to be treated was placed in a 500-ml beaker, into which was poured 300-cc of distilled water. To this was added 15 grams of powdered oxalic acid and a cylinder of sheet aluminum, the diameter of which was slightly less than that of the beaker, and the length of which was great enough to extend approximately an inch above the level of the solution in the beaker. After 20 minutes of gentle boiling, the aluminum cylinder was removed and the liquid decanted from the beaker. The sediment was washed, agitated, and decanted repeatedly, until the supernatent wash water remained clear. After the final washing, the sediment was dried for five hours at 105°C., cooled in the atmosphere of the laboratory, and weighed. No attempt was made to determine the amount of iron removed during treatment, but if this information should be desired, the solution and washings may be retained and analyzed, care being taken to include the precipitate of yellow ferrous oxalate which forms on the aluminum cylinder.

The amonium tartrate-aluminum treatment used in this study is an adaptation of Dion's modification of the Jeffries method (Dion, 1944). In this case hydrogen is produced by the action of ammonium tartrate on metallic aluminum, which, according to Dion, is less destructive to the structural lattices of the clay minerals than are other methods, but at the same time is efficient in removing free iron oxides. To a beaker containing 10 grams of the sample was added 100 cc of a 10 per cent solution of ammonium tartrate. The aluminum cylinder was introduced into the beaker and the solution boiled gently for 20 minutes. The cylinder then was removed, the solution decanted, and the sediment washed until the wash water remained clear. After drying for two hours at 105°C., the sample was cooled in the laboratory atmosphere and weighed.

CONCLUSIONS

Qualitative data resulting from this study, summarized in tables 1 and 2, indicate that for removing coatings of iron oxide from sand grains or crushed mineral fragments, a modification of Jeffries' oxalic acid-aluminum treatment is the most effective of the methods investigated. Other materials which often form an integral part of a clastic sedimentary deposit are affected only slightly by this treatment. Although carbonates are not readily dissolved, there is no objectionable calcium precipitate formed by the reaction, as is the case with most of the other reagents. The method would not be satisfactory for disaggregating a sandstone with a carbonate cement. Gentle boiling in a 10 per cent solution of oxalic acid is also an effective method of removing iron oxide, but as in the case where the reduction of the iron is by means of hydrogen produced by the action of oxalic acid on aluminum, carbonate cement is not readily dissolved.

If it is necessary to remove calcium carbonate as well as iron oxide, gentle boiling in 20 percent phosphoric acid is to be recommended. However, with this treatment any apatite present in the sample will be attacked severely, and a finely crystalline precipitate of calcium phosphate might prove objectionable. With the other reagents tested, removal of iron oxide is incomplete, and formation of calcium precipitate, especially with citric acid, is so pronounced as to interfere seriously with microscopic examination.

TABLE 1.—*Per cent change in weight of sand and mineral grains resulting from treatment to remove iron oxide*

Mineral	Reagent						
	Citric acid	Tartaric acid	Oxalic acid	Phosphoric acid	Oxalic acid-aluminum	Ammonium tartrate-aluminum	Ammonium tartrate
Apatite	−13.3	−14.4	No effect	−19	−0.85	−1.1	Not treated
Biotite	No effect	No effect	No effect	No effect	−0.85	Not treated	Not treated
Calcite	+77	− 6.1	−0.6	−34.5	−0.58	+1.1	Not treated
Dolomite	−21.5	−24.8	−2.3	−54	−3.4	−2.7	Not treated
Sandstone	− 3.3	− 4.2	−4.2	− 3.8	−4.8	−4.1	−3.6

TABLE 2.—*Visible changes in sand and mineral grains resulting from treatment to remove iron oxide*

Mineral	Reagent						
	Citric acid	Tartaric acid	Oxalic acid	Phosphoric acid	Oxalic acid-aluminum	Ammonium tartrate-aluminum	Ammonium tartrate
Apatite	Slightly rounded	Slightly rounded	Severely rounded and clouded	Slightly rounded and clouded	Severely rounded and clouded	Some clusters of finely crystalline aggregates	Not treated
Biotite	No effect	No effect	No effect	Opaque masses in flakes	No effect	Not treated	Not treated
Calcite	Abundant crystalline precipitate replacing original fragments	Fragments coated with crystalline precipitate	Slightly rounded	Fragments reduced in size. Abundant crystalline precipitate	Slightly rounded	Fragments partly coated with crystalline precipitate	Not treated
Dolomite	Moderately etched	Slightly etched	Clouded	Severely etched	Clouded	Luster dulled, slightly rounded	Not treated
Sandstone	Grains colored brownish-red	Grains colored brownish-red	Iron oxide removed. Grains bright and clear	Most of iron oxide removed. Grains bright and clear	Iron oxide completely removed. Sand is pure white, grains bright and clear	Grains colored light brown	Grains colored yellow-brown

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REVIEWS

Report of the Committee on a Treatise on Marine Ecology and Paleoecology, 1948–1949; Harry S. Ladd, Chairman; Gordon Gunter, Vice Chairman for Biology, Kenneth E. Lohman for Geology, Roger Revelle for Oceanography, Published by Division of Geology and Geography, National Research Council, Washington, D. C., pp. 1–121, 19 figures, Price $1.00.

This is the annual report of the above named committee. It contains four items as follows: (1) "Introduction," (2) progress of preparation of a "Treatise on Marine Ecology and Paleoecology," (3) a summary of "Current Activities" connected with the work of the committee, and (4) a list of "Recent Publications" connected with or related to the field of the committee.

The topic dealing with the "Treatise on Marine Ecology and Paleoecology" presents a classification of marine environment which has little fundamental difference from classifications previously presented by various students except that the littoral life zone is made to include the "Supratidal" and the "Neritic" life zones and is also divided into the "Eulittoral" and "Sublittoral" zones at the depth of 50 meters. Waters beyond the neritic (depth of 200 meters) are designated "Pelagic" and "Bathypelagic" and both are included in the "Nectoplanktonic."

Item 3, current activities, has reports dealing with ecologic and paleoecologic work in "Eastern United States," "Middle United States," "Western United States," and "Outside the Continental United States." The committee has not included results of any work done in lands other than those under the jurisdiction of the United States.

In addition to Items 1 to 4, the most interesting part of the report presents completed units of the treatise as Item 5. This has four subitems of which "Selected Analyses from the Geologic Record" on the "Paleoecology of the Cambrian in Montana and Wyoming" by Christina Lochman and "Paleoecology of the Jurassic Seas in the Western Interior of the United States" by Ralph W. Imlay are number 1. Numbers 2 and 3 are "Annotated Bibliography of Marine Ecology" with "Ecology of Nonalgal Marine Plants" by Roland W. Brown and "Annotated Bibiliography of Paleoecology" with considerations of the "Agnatha" by George M. Robertson, and subitem 4 on "Types of Occurrence and Position of Bryozoa in Late Paleozoic Sediments of the Midcontinent" by Maxim K. Elias.

Items 1 to 4 are presented in 30 pages. The balance of the report deals with the contributions of Christina Lochman (pp. 31–71), Ralph W. Imlay (pp. 72–104), Roland W. Brown (pp. 105–110), George W. Robertson (pp. 111–116) and Maxim K. Elias (pp. 117–121).

In any attempt to determine environmental condition from the lithified products of sedimentation, the contained organisms, the allogenic and authigenic minerals, and such other data as may be available much depends on the experience of the interpreter in study of existing environments, critical training under competent students of environments, and the subjective temperament of the interpreter. The reviewer considers that Prof. Robertson has shown a proper attitude in his discussion of the Agnatha. Miss Lochman's contribution is interesting and should be carefully read, but there are parts which the reviewer would question. Galliher's interpretation of the origin of glauconite seems to be completely accepted and the environment of deposition of the Upper Cambrian and Lower Ordovician is stated to have been

of normal marine waters. As applied to Wisconsin the reviewer is of the opinion that at times the Cambrian waters of deposition were not normal marine but may actually have been fresh. The reviewer has also studied slides prepared by Galliher and is of the opinion that much remains to be proven. Worm trails are frequently reported, but there is no evidence presented to prove that worms were concerned. Entire formations and parts of other formations contain no fossils certainly identifiable as marine, but these are assigned to a normal marine origin. The reviewer considers that conclusions are too positive in places. Dr. Imlay's paper on the Jurassic represents a somewhat more conservative approach. Dr. Brown's contribution suffers from absence of much data in the field of nonalgal marine plants, but a good bibliography is appended. Dr. Elias's contribution adds somewhat to the little that seems to be known of the ecology of the Bryozoa.

This report should be read by all interested in ecology and paleoecology. While most will find points of disagreement, much will be learned, and some new point of view may be garnered.

W. H. TWENHOFEL

Elements of Oil Reservoir Engineering by Sylvain J. Pirson, pp. 441, 215 figures, McGraw-Hill Book Co., Inc., New York, 1950, Price $6.50.

It must be obvious that if sedimentary petrographers are to play their proper role in the study of oil reservoir rocks they must make themselves familiar with the requirements of the petroleum engineer. The danger of losing this aspect of sedimentary petrography has been emphasized recently by an attempt to sever from petrology the study of properties and behavior of reservoir rocks under the term petrophysics (Archie, 1950). It must be noted that despite the separation of another such branch, geophysics, it has been the published aim of most petroleum experts to attempt a coordination of geology and geophysics for the benefit of both in the exploration for oil reservoirs. It would be unwise, therefore, if petrographers allowed a schism—obviously of doubtful advantage to develop in their field.

In this respect Pirson's textbook represents a milestone in the acceptance of petrography as an integral part of petroleum geology and engineering. The first fourteen pages present a simplified version of Krynine's classification of sedimentary rocks with idealized figures illustrating the mineral composition and genesis of the different types. It is noteworthy that although the quartzite-limestone, graywacke (low rank or common) and arkose are discussed, no mention is made of the high rank (feldspathic) graywacke presumably because the latter is a relatively rare sedimentary rock and an exceedingly rare oil reservoir rock.

Other features of interest to sedimentary petrographers in Pirson's text include the classification of reservoirs (Chapter 2, pp. 76–79) in which sedimentary environment plays a prominent part, and the explanation of electric and radio-active logging. The former in particular is given a very up-to-date treatment with due emphasis on the part played by formation composition (Mounce potential) in determining the dominant portion of the measured electrical potential difference.

A stimulating discussion of an aspect of "migration" not usually emphasized is also given on pp. 204–207 where geological (petrological) factors are held responsible for the characteristics of the fluids in oil reservoirs, while the control of edgewater drives by the type of rock which forms the reservoir is hinted at on p. 234.

Various other features concerning the importance of the type of sedimentary rock to the properties and behavior of oil reservoirs occur throughout the text and suggest that with adequate investigation of these rocks by competent petrogra-

phers sedimentology may play a much more important role in future petroleum engineering. It is, however, essential that the petrographers should be reasonably cognizant of the kind of information necessary and to this end "Elements of Oil Reservoir Engineering" should be a valuable guide and reference source for sedimentary petrographers interested in the field of reservoir rock characteristics and behavior.

J. C. GRIFFITHS

ARCHIE, G. E., *1950.* Introduction to petrophysics of reservoir rocks: Am. Assoc. Petroleum Geologists Bull., vol. 34, no. 5, pp. 943–961.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 20, NO. 3, PP. 180–181
SEPTEMBER, 1950

ANNOUNCEMENT

OPPORTUNITIES FOR LECTURING AND RESEARCH ABROAD UNDER THE FULBRIGHT PROGRAM FOR THE ACADEMIC YEAR 1951–52

Approximately 300 awards for United States citizens to serve as visiting lecturers or to engage in research in institutions of higher learning abroad during the academic year 1951–52 have been announced by the Department of State under the provisions of Public Law 584 (79th Congress), the Fulbright Act.

Many of the awards are open to applicants in the field of geology. Countries now participating in the program are Australia, Belgium-Luxembourg (including the Belgian Congo), Burma, Egypt, France, Greece, India, Iran, Italy, Netherlands, New Zealand, Norway, the Philippines, Turkey, and the United Kingdom, including the British Colonial Dependencies.

In addition to the large number of awards offered without specification of subject or sponsoring institution, attention is called to the following specific opportunities in geology and related fields at certain designated institutions abroad.

BURMA.—The visiting scholar would be attached to the University of Rangoon, which is especially interested in sponsoring a specialist in stratigraphy, paleontology, or economic geology. The academic year begins in late June and ends in March. The successful candidate should also be prepared to give invitational lectures in his field of specialization.

EGYPT.—Farouk I University in Alexandria has expressed an interest in receiving a visiting lecturer in paleontology. Additional details regarding this opportunity are expected in the near future.

NETHERLANDS.—Although no particular aspect of the subject is given preference, geology is among the subjects in which a visiting lecturer would be welcomed at the University of Utrecht.

NORWAY.—The University of Oslo has included geology and mineralogy among those subjects in which it offers the greatest opportunities to American research scholars.

NEW ZEALAND.—*Offshore Sedimentation:* The Museums Association of New Zealand has proposed that an American scholar participate in an investigation into the origin and distribution of the sediments at present forming on the continental shelf around New Zealand.

Oceanography: The Museums Association of New Zealand is also interested in sponsoring research in oceanography as a part of the Pacific-wide program of oceanographic research recommended by the seventh Pacific Science Congress. Although a specialist in marine biology or an experienced director of oceanographic research would find more of interest in the way of current research in New Zealand, the opportunity is also open to a specialist in the physio-chemical, meteorological or physiographic aspects of oceanography.

Geophysics: The Department of Scientific and Industrial Research offers an opportunity to an American geophysicist with a background in engineering to collaborate with a team of New Zealand scientists on investigations of the Rotorua Thermal Area. The geophysical section will carry out gravimetric, electrical, airborne magnetometer and seismic surveys, and investigations into drilling and thermal conductivity and specific heat of rocks.

The academic year in New Zealand begins in March and ends in December.

PHILIPPINES.—Although not on its priority list, economic geography has been included by the University of Philippines in the list of alternative subjects in which a visiting lecturer from the United States is desired. The academic year begins in late June and ends in March.

UNITED KINGDOM.—Most of the

awards available for lecturing and research in the United Kingdom are offered without specification of subject or receiving institution. The following universities or university colleges, however, have indicated an interest in receiving American lecturers or research scholars in geology: Aberdeen, Birmingham, Bristol, Cambridge, Liverpool, London, Manchester, Nottingham and Southampton. Since it is desirable that American grantees be distributed widely throughout the British university system, applications made with a view to attachment at universities other than Cambridge, London and Oxford are especially encouraged.

OTHER COUNTRIES.—Programs for Australia will be announced by the Department of State in the near future. It is anticipated that opportunities will be provided for research in invertebrate paleontology.

Most of the countries participating in the Fulbright program—especially France, Italy and the United Kingdom—provide a number of awards which are not restricted as to subject or receiving institutions. University teachers or postdoctoral scholars in the field of geology should not hestitate to apply for undesignated awards, especially for research, in countries in which they are interested.

The awards are made under Public Law 584 (79th Congress), the Fulbright Act. Awards are ordinarily made for one academic year, although in exceptional cases applications will be considered for periods of not less than six months. Grants for teaching or research usually include round-trip transportation for the grantee, a maintenance stipend, including certain allowances for dependents, and a small supplemental allowance for travel and equipment purchasable abroad, if necessary. The grants are made in the currency of the country to which the grantee is going and are not convertible into dollars.

No award will be made for teaching or research in more than one country in any one year and only one application may be filed each year. Applicants may indicate an alternate country, however, if the proposed activity can be satisfactorily completed in more than one country.

The closing date for filing applications for awards for lecturing and research for the academic year 1951–52 is October 15, 1950. Requests for application forms and for further information concerning opportunities for visiting lecturers, research scholars and specialists should be addressed to the Committee on International Exchange of Persons, Conference Board of Associated Research Councils, 2101 Constitution Avenue, Washington 25, D. C.

Note: There are many openings for predoctoral graduate study and for elementary and secondary school teaching in countries participating in the Fulbright program. Inquiries regarding opportunities for graduate study should be addressed to the Institute of International Education (2 West 45th Street, New York 19, New York) and regarding awards to elementary and secondary school teachers to the Division of International Educational Relations, United States Office of Education (Federal Security Building, Washington 25, D.C.).

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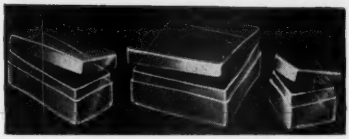

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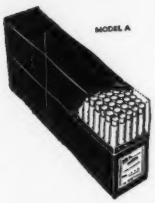

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